Assessing the Climatic Suitability of Bambara Groundnut as an Underutilised Crop to Future Climate Projections in Sikasso and Ségou, Mali

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Declaration

I write to declare that I know the meaning of plagiarism and the work in the dissertation is mine, also all sources used have been duly acknowledged.

Abstract

This study evaluates how future climatic projections will affect the suitability of bambara groundnut (*Vigna subterranean*(L) Verdc.), a type of underutilised crop in Sikasso and Ségou, southern Mali. This study was performed using a simulation approach, which considered the potential changes in suitability due to projected changes in two climate variables; temperature and precipitation. Monthly outputs of the two climate variables from 10 CORDEX bias-corrected regional projections under the Representative Concentration Pathway (RCP) 8.5 were applied. The suitability index range of bambara groundnut was projected, using the Ecocrop suitability model, considering three time periods: historical (1975-2005), near-term (2011-2040), and end of century (2070-2099).

The results of this study showed that the model captured a long planting window for the crop in the regions across the time periods. With the projected increase in future climatic conditions, the suitability index range of bambara groundnut is projected to increase across the months suitable for planting the crop. Furthermore, Sikasso is projected to maintain a high suitability index in the near-term, and by the end of century, Ségou is expected to experience a potential increase in suitability index range and suitable areas, especially by the end of century. The results indicate that the CORDEX projections and suitability modelling technique applied in the study captured well the suitability of bambara groundnut in the regions which can help the farmers in making planting decisions. These results suggest an opportunity for optimal utilisation of the crop in the regions, as with a long planting window and expansion in suitable areas, farmers in the regions can plant multiple times and have more suitable areas to cultivate.

This study contributes to improving the decision-making surrounding the promotion of underutilised crops as part of the strategy for climate-resilient agriculture and food security in Sikasso and Ségou.

Keywords: Bambara groundnut, Ecocrop, CORDEX, crop suitability, underutilised crop

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Dedication

To Chiduruo and Mmachukwu Okpala

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List of Abbreviations

AEZ - Agro-Ecological Zone

CFSVA - Comprehensive Food Security and Vulnerability Analysis

FAO - Food and Agriculture Organization

GCM - Global Climate Model

GHG - Greenhouse Gas

ICUC - International Centre for Underutilised Crops

IFAD - International Food for Agricultural Development

IPCC - Intergovernmental Panel on Climate Change

IPES - International Political Economy Society

MAGICC - Model for the Assessment of Greenhouse-gas Induced Climate Change

NASAC - Network of African Science Academies

NAS - National Academy of Science

NAPCCA - National Action Plan on Climate Change Adaptation

NUS - Neglected and Underutilised Species

SCENGEN - Regional Climate Scenario Generator

SSA - Sub Saharan Africa

UNCTAD - United Nations Conference on Trade and Development

UNEP - United Nations Environment Programme

UN - United Nations

Chapter 1: Introduction

This chapter describes the context of the study, starting with a general background on climate change and population in Mali. It goes further to offer a brief introduction to agriculture and food security in the country and the concept of neglected and underutilised crop species. This chapter also describes the motivation and aim of the study, the processes used in achieving this aim, and finally an outline of the study.

1.1 Climate change

Since 1950, the global mean surface temperature has risen by 1.3°C, at an estimated increase of 0.2°C per decade due to a rise in carbon emissions and an accumulated global concentration of greenhouse gases (GHGs) (Lobell, Schlenker and Costa-Roberts, 2011). These emissions are driven by factors such as extensive economic activities and population growth (IPCC, 2014). Africa is one of the regions predicted to be the most vulnerable to climate change, despite its economic activities only marginally contributing to the accumulated global concentration of greenhouse gases (GHGs) (IPCC, 2007). Furthermore, evidence suggest that an increase in the global average air and ocean temperatures are likely to result in an increase in mean surface temperature, and a rise in the global average sea level, amongst other consequences (IPCC, 2014). This has prompted a proposition on intensifying actions for a sustainable low carbon future and combating climate change, which saw the establishment of the 2015 Paris Agreement. The 2015 Paris Agreement established climatic thresholds by creating a long-term temperature goal of holding the increase in global average temperature to below 2°C while exploring efforts to limit further increase to 1.5°C (UNFCCC, 2015).

There is a high confidence prediction that the rise in global warming of 1.5 to 2°C will increase climate-related risks on crop production and food security in Africa (Conway *et al.*, 2007; Wheeler and von Braun, 2013; Krishnamurthy, Lewis, and Choularton, 2014). In addition, multiple studies on climate change over Africa predicts that the region will experience extreme weather conditions (Collier *et al.*, 2008; Cooper *et al.*, 2008; Songok *et al.*, 2011). These conditions are projected to pose a severe threat to crop production, and increase human and household vulnerability to catastrophic climate-related hazards (Heltberg, Jorgensen, and Siegel, 2008; Schleussner *et al.,* 2018). Developing countries are more vulnerable to these threats because of limited capacity to adapt, direct adverse effect on climate-sensitive sectors such as agricultural sector and high agricultural dependence (Collier, Conway and Venables, 2008) triggering food scarcity and price spikes among the growing population (FAO, 2008).

1.2 Population

The human population is projected to increase to about 9 billion by 2050, and with an increase in population comes a rise in food demand (Tomlinson, 2013; Grafton, Daugbjerg and Qureshi, 2015). Furthermore, the numbers of people affected by food insecurity is projected to continue to rise (Misselhorn *et al.*, 2012). Over the years, this number has grown from 775 million people in 2014 to approximately 851 million in 2016, indicating that globally at least one in nine people are food insecure (FAO, 2017).

Between 1990 and 2010, the Mali population has increased by 74% with Sikasso, Koulikoro, and Tombouctou regions having the most substantial population increases (Funk *et al*., 2012). In 2011, Mali had an estimated population of about 14.2 million, which increased to 18.4 million in 2018 (CIA, 2019). However, approximately 70% of this population lives in rural areas, with most residing in southern Mali (e.g. Koulikoro, Ségou, N'Tarla, Sikasso, Bamako, Mopti).

1.3 Agriculture and food security in Mali

1.3.1 Agriculture in Mali

Agriculture is the dominant source of food and livelihood for more than 80% of Mali's population, particularly for people living in rural areas (Butt *et al.*, 2005), mostly dominated by smallholder farmers and contributes to up to 45% of the country's gross domestic product (GDP) (Ebi *et al.*, 2011). The agricultural system in Mali varies from agro-pastoralism in southern Mali to pastoralism in northern Mali. In southern Mali, more than 70% of the households are engaged in various agricultural practices, especially the cultivation of various types of crops and depend mostly on rainfed agriculture (Kergna and Dembele, 2018). Of the agricultural products, 87% are mainly for household consumption (CFSVA, 2005). However, despite this high rate of farming activities, crop production remains low due to factors such as pest and diseases (Legg and Togola, 1993; Settle *et al*., 2014), low soil fertility (Kaya and Nair, 2001) and climate change (Traore *et al*., 2013). These factors are expected to increase the risk to food and nutrition insecurity in Malian households.

1.3.2 Food security in Mali

Describing the level of food insecurity in West Africa, Von Grebmer *et al.* (2014) indicate that countries like Mali experience a high rate of nutritional insecurity and hidden hunger and described hidden hunger as a form of hunger that is ignored or overshadowed, often related to energy deficits, also known as micronutrient deficiency relative to the world average. In Mali, food insecurity is becoming a profound issue and particularly evident in the rural areas (Generoso, 2015), this is due to factors such as low crop yield as a result of climate variability, evolution of crop-livestock farming systems, demographic pressure, and stress from the cotton sector crisis (De Bruijn *et al.*, 2005; Baquedano *et al*., 2010). In 2005, vulnerability analysis and mapping (VAM) estimated that about 6.2 million people in Mali were food insecure and vulnerable (CFSVA, 2009). Similarly, FAO (2007) estimated that over a quarter of Mali's population is malnourished as a result of low diet quality resulting from undiversified, and unbalanced food with slight improvement since 1990. This state of food insecurity has placed Mali in category 4 of the Food and Agriculture Organization (FAO) countries at risk of hunger ranking, with 5 being the highest (FAO, 2007).

Mali often experiences two periods of food crises. The first period occurs at least once in three years, mostly over the northern part of the country, as a result of repeated locust invasion and drought that threatens crop yield and the second food crises period occurs at least every year between July (planting season) to September (harvesting season) and often referred to as the lean period (CFSVA, 2005; Sidibe *et al.*, 2015). The food insecurity situation in Mali spreads across the country. However, the northern part of Mali (Gao, Kidal, the lake area of Tombouctou), south of Kayes and Koulikoro, areas in Mopti (Niger delta, Douentza Cercle and Dogon Plateau), and north of Ségou are the most food-insecure regions in the country.

1.4 Neglected and underutilised crop species (NUS)

The human diet has become more homogenous in the last 50 years, attributed partly to the focus of the human diet on a few staple crops that are being cultivated and consumed (Khoury *et al.,* 2014). These less cultivated and consumed crops are often referred to as neglected and underutilised crop species (NUS). The neglected and underutilised crop are also referred to as minor, promising, traditional, new, underutilised, under-researched, underexploited, niche, or orphan crops (Padulosi *et al.*, 2002; Zepeda and Cohen, 2006; Massawe *et al.*, 2015).

There is no consensus as to the definition of neglected and underutilised crop species. Nevertheless, for this study, these crop species will be referred to as underutilised crops and defined as crops that have low cultivation and utilisation levels (Azam-Ali, 2010). Some examples of underutilised crops include livingstone potatoes, fonio, bambara groundnut, and dika nut. Underutilised crops are mostly cultivated by smallholder farmers, and are known to be highly adaptable to agroecological niche areas, have the potential of ensuring food security, creating new markets, enhancing crop diversity and improving nutrition, and can be produced with low external input (Berchie *et al.*, 2012; Ebert, 2014; Chivenge *et al.*, 2015; Massawe *et al.*, 2015; Gulzar and Minnaar, 2017; Mayes et al., 2019).

1.5 Motivation of the study

Changes in future climatic projections are expected to affect different aspects of agricultural crop production including crop yield, growth, and suitability. Also, one of the significant challenges currently facing the agricultural crop system in Mali is the need to provide healthy and nutritious food for a growing population under the changing climatic conditions based on a few staple crops (Giannini et al., 2017). With studies projecting a reduction in the suitable areas available for the planting of these staple crops due to the changes in future climatic conditions, the impact of these conditions on the suitability of underutilised crops remain unknown. Thus, the principal motivation for this study is to assess the climatic suitability of underutilised crops, with a focus on bambara groundnut. The goal is to understand the suitability and cultivation potential of the crop under future climatic projection in Mali to help guide the decisions on the crop towards its optimal utilisation and the adequate utilisation of agricultural lands. This study will further help to identify the potentials of underutilised crops as an adaptation strategy that can contribute to complementing the food system and increase crop and food diversity.

1.6 Research aim and objectives

1.6.1 Aim

This study aims to assess the past to future climatic suitability changes of bambara groundnut in Sikasso and Ségou, Mali.

1.6.2 Objectives

The specific objectives are to:

1. Examine underutilised crops and their benefits to the agricultural and food sector.
2. Evaluate the seasonal changes in the suitability of bambara groundnut under past and future climate conditions.
3. Assess the spatial suitability changes of bambara groundnut under past and future climate projections.

1.7 Outline of the dissertation

Chapter 1 presents an introduction to the integral concepts of this dissertation: agriculture, climate change, and food security. It also offers an introduction to neglected and underutilised crop species while also describing the motivation, aim, and objectives of the study.

Chapter 2 presents an overview of underutilised crops and their potential benefits in the agricultural sector as well as a dedicated overview of bambara groundnut. Furthermore, it reviews the climate system over West Africa and Mali and further reviews past studies on crop modelling and the impact of climate change on crop production, thereby addressing objective 1.

Chapter 3 describes the study area in Sikasso and Ségou regions, southern Mali. It also provides a detailed description of the climate datasets - the Climate Research Unit (CRU) data and 10 CORDEX data used in this study. It also describes the crop model (Ecocrop) set up and the suitability simulation approach of bambara groundnut to past and future climate conditions in Sikasso and Ségou regions.

Chapter 4 contains the results of seasonal and spatial suitability of bambara groundnut in Sikasso and Ségou under the past (baseline and historical) and then projected suitability under the future climate (near term and end of century). This chapter addresses objectives 2 and 3

Chapter 5 contains discussions on the impact of future climatic projections on the suitability of bambara groundnut in Sikasso and Ségou.

Finally, Chapter 6 concludes on the climatic suitability of bambara groundnut in Sikasso and Ségou and makes recommendations that could further benefit the inclusion and utilisation of the crop as a strategy towards improving the food system.

Chapter 2: Literature review

This chapter provides an overview of neglected and underutilised crop species (NUCS), a background on bambara groundnut and its importance, the climate in West Africa, and the climate system classification over Mali. This chapter further reviews different crop modelling techniques and their application in crop growth and yield simulation as well as previous studies on the impact of climate change on crops in Mali.

2.1 Overview of neglected and underutilised crop species (NUCS)

The number of agricultural crops that exist in the agricultural crop system is well documented in the literature. For instance, approximately 300,000 known crop species exist in the world, with about 30,000 said to be edible (Garn and Leonard, 1989). However, in recent times, there has been a decline in the number of crop species as out of the 30,000 edible plants, only about 7000 are collected and cultivated as food (Chivenge *et al.*, 2015). Moreover, despite nearly 7,000 crop species being grown as food, more than 90% of the global food production depend mostly on less than 30 crop species with the primary crops being rice, maize, millet, and wheat and 10% based on other crops (Collins and Hawtin, 1999). This increased dependence on food production on these primary crop species has influenced the utilisation of many crop species prompting the collective name neglected and underutilised crop species (NUCS) (hereafter referred to as underutilised crops).

The Biodiversity International Centre for Underutilised Crops (ICUC) and the United States of America (USA) National Academy of Science (NAS) has identified over 200 species of underutilised crops in different eco-geographical regions of the world (Gupta *et al*., 2013). Some examples of the underutilised crops include about 29 cereals (e.g., Finger millet (*Eleusine coracana*), Foxtail millet (*Setaria italica*), Fonio (*Digitaria exilis*), Tef (Eragrostis tef)), 27 legumes (e.g., Bambara groundnut (*Vigna Subterranea*), Africa yam bean (*Sphenostylis stenocarpa*), Kresting's groundnut (*Kerstingiella geocarpa*)), 25 roots and tuber crops (e.g., Yocn (*Smallanthus sonchifolius*), Livingstone potato (*Plectranthus esculentus*)), 52 fruits and nuts (e.g., Natal plum (*Carissa edulis*), Dika nut (*Irvingia gabonensis*), Jackfruit (*Artocarpus heterophyllus*), Ber (*Ziziphus* sp.)), 39 vegetables (e.g., Amaranth (*Amaranthus* sp.), Moringa (*Moringa oleifera*), Boscia (*Boscia coriacea*)) and 5 fibers and pulp yielding plants (e.g., Jute (*Corchorus olitorius*)) (Chweya and Eyzaguirre, 1999).

Table 2.1: List of different underutilised crops, origin and nutritional values

Name of Crop	Type	Nutritional Value (high, medium, low)	Origin (countries or continents)	Related Literatures
Fonio (*Digitaria exilis*)	Cereal	High	West Africa	Koreissi-Dembélé., et al 2013, Jideani., A 2012, Koroch *et al.,* 2013
Finger Millet (*Eleusine coracana*)	Cereal	Medium	Africa, Asia	Gupta *et al*., 2013, Collins and Hawtin, 1999.
Bambara groundnut (*Vigna Subterranea*)	Legume	High	Africa	Mayes *et al.*, 2019, Karunaratne *et al*., 2010, Azam-Ali *et al*., 2001.
Africa yam bean (*Sphenostylis stenocarpa*)	Legume	High	Africa	Adewale and Dominique, 2009, Oagile, Davey and Alderson, 2008
Livingstone potato (*Plectranthus esculentus*)	Tuber	High	Africa	Kujeke et al., 2019, Cassandra, 2006, Hannweg, Steyn and Bertling 2016
Dika nut (*Irvingia gabonensis*),	Fruit	Medium	West and Central Africa	Leakey *et al*., 2005, Kumar, 2007.
Jackfruit (*Artocarpus heterophyllus*)	Fruit	Medium	Asia	Khan et al., 2009, Tulyathan *et al*., 2001, Baliga *et al*., 2011
Amaranth (*Amaranthus sp.*)	Vegetable	High	South and Central America, Asia and Africa	Achigan-Dako *et al*., 2014, Rastogi and Shukla, 2012

Moringa (*Moringa oleifera*)	Vegetable	High	Asia	Foidl, Makkar and Becker, 2001, Anwar *et al.*, 2006, Moyo *et al.*, 2011.
Jute (*Corchorus olitorius*)	fiber	Medium	Asia	Loumerem and Alercia 2016, Islam, 2013, Ndlovu and Afolayan, 2008.
Kresting's groundnut (*Kerstingiella geocarpa*),	Legume	Medium	Africa	Ayenana and Ezin 2016, Adu-Gyamfi *et al.,* 2011, Assogba *et al.,* 2015.

Due to the high potential agricultural and economic as well as high nutritional values, underutilised crops are currently being promoted by different agricultural institutions and initiatives. For instance, on the global scene, the 68th United Nations General Assembly in a bid to enhance food and nutrition security declared 2016 the International Year of Pulses, with the aim of creating and promoting unique opportunities for improving the utilisation of pulse crops within the agricultural and food system (United Nations, 2013). Also, for improvement in the utilisation, conservation, and development of underutilised crops in the agricultural sector, the international community through the Global Plan of Action for the Conservation/Sustainable Utilisation of Plant Genetic Resources for Food and Agriculture alongside the Global Forum for Agriculture Research (GFAR) in 2002 established a German-supported facilitation unit for underutilised crops (Frison, Omont, and Padulosi, 2000).

Other initiatives include the project of Bioversity International[1] which promotes underutilised crops (e.g. Fonio, Bambara groundnut, Finger millet, Amaranth or Moringa), transformative agrobiodiversity innovations and management practices towards protecting agricultural biodiversity, as well as the use of crop diversity for climate change adaptation. Also, BAMLINK the third European Union (EU) project established in a bid to improve the knowledge and research on genetics and agronomy of bambara groundnut in Africa and India (Mayes *et al.*,

[1]www.bioversityinternational.org

2009), and the Crop for the Future Institute[2] which promotes innovative research on underutilised crops that will be beneficial to societal demand.

Alongside the promotion of underutilised crops by agricultural institutes and initiatives, the crops are beginning to gain attention from researchers, especially in developing countries, advocating for an increase in transdisciplinary research on the crops (Padulosi *et al.*, 2002; Azam-Ali, 2010; Mabhaudhi *et al.*, 2017). Such studies on underutilised crops can serve as a transformational tipping point that could drive rapidly diversified and sustainable changes in the food system and economy over the next decades. Some examples of already existing transdisciplinary studies on underutilised crops include studies on the willingness of consumers to purchase an underutilised African vegetable in South Africa (Senyolo, Wale, and Ortmann, 2014), the study by Ayanwale *et al.* (2011), on the marketing chains of underutilised crops in southwest Nigeria, dietary studies on underutilised corps (Okpuzor *et al.*, 2010; Ofosu *et al.*, 2017), and the impact of different environmental factors on underutilised crops (Klu G.Y.P *et al.*, 2001; Berchie *et al.*, 2012). These studies documented and examined underutilised crop potentials, their sensitivity to climate change, pests and diseases, their socio-economic importance, and their potential role in food systems.

2.1.1 The origin of bambara groundnut

Bambara groundnut (*Vigna subterranea* (L.) Verdc.) is an indigenous, leguminous underutilised crop. Despite the debate about the origin of the crop, it is argued to have originated from the Bambara tribe, a place near Timbuktu in Central Mali, West Africa, hence the name bambara (Holm and Marloth, 1940). Though originating from Mail, the crop is widely cultivated and distributed across different countries in Africa such as Burkina Faso, Nigeria, South Africa, Namibia, Guinea, Mali, Niger, Zimbabwe, Zambia, and Malawi (Suwanprasert *et al.*, 2006). Bambara groundnut belongs to the fabacean family, this family includes other leguminous crops like soybean (*Glycine max*), cowpea (*Vignau nguiculata*), dry beans (*Phaseolus vulgaris*), and mungbean (*Vigna radiata*) and is an ancestral spring of *V.*

[2]www.cffresearch.org

substerrenea var. *spontanea* (Goli,1997). Also, bambara groundnut is one of the most popular underutilised crops in Mali.

Bambara groundnut has distinctive local names among different countries and communities. For instance, it is traditionally known as Gurjiya or Kwaruru (Hausa, Nigeria), Epa Roro (Yoruba, Nigeria), Togo azigokui (Togo), Nyimo (Zimbabwe), jugo beans or Indlubu (South Africa), and Ntoyo ciBemba (Zambia). As an underutilised crop, bambara groundnut has no established variety, rather exists mostly as a landrace (Redjeki, Mayes and Azam-Ali, 2013). A landrace is a local species selected through a traditional method without the influence of modern breeding technologies (Karunaratne *et al*., 2015). Several landraces of bambara groundnut exhibit distinct characteristics depending on its agroecological origin and the landraces are named based on their morphological features such as testa colour or place of origin (Massawe *et al.*, 2005), and are commonly a form of identification for the seeds (Muhammad, Mayes, and Massawe, 2016). Some common examples of bambara groundnut landraces are DipC, S19-3, Uniswa Red- UN, and about 1700 accessions at the International Institute of Tropical Agriculture (IITA) gene bank (Nigeria) (Figure 2.1).

Figure 2.1: Picture of different accessions of bambara groundnut (source: IITA Nigeria Genetic Resources Gene bank).

2.1.2 Bambara groundnut production in West Africa

The cultivation of bambara groundnut is mostly undertaken by subsistence farmers mostly women, primarily for local utilisation and consumption, often resulting in low production and market value of the crop despite its enormous potentials (Ibrahim *et al.*, 2018). The total production rate of bambara groundnut in Africa was estimated to be over 330,000 metric tonnes per year in 1994, with Nigeria as the leading producers with 100,00 metric tonnes. However, in 2008 bambara groundnut production was reported to be about 100,000 metric tonnes in west Africa, with production occurring mostly in Mali, Democratic Republic of Congo, Cameroon, and Burkina Faso; Burkina Faso was the leading producers with 44,712 metric tonnes (FAO 2009). The current production rate for the crop is unknown due to data limitation. Hence, the recent attention on the crop from researchers pushing for more research studies on the crop (Cleasby *et al*., 2016; Mabhaudhi *et al.*, 2017).

2.1.3 Nutritional importance of bambara groundnut

Legumes constitutes a high level of protein, a high proportion of starch or oil depending on the crop, significant amount of vitamins, minerals and dietary fibre (Angioloni and Collar, 2012). A rich indigenous nutritional knowledge exists on bambara groundnut crops. The crop is often grown for food, oil, fodder, medicinal purposes, and produces food with exceptionally high nutritional qualities (Bamshaiye, Adegbola, and Bamishaiye, 2011). On average, bambara seed consists of 17.4-25.2% protein, almost 20% fibre, 6.5% oil, 42-65% carbohydrate, and on dry weight basis 6-7.9% lipid. It also has a relatively high lysine of 6.8% and methionine of 1.3% (Brough and Azam-Ali, 1992; Bamshaiye, Adegbola, and Bamishaiye, 2011). Bambara groundnut also plays a vital role in building and maintaining a solid foundation for the good health of many in rural communities (Koné *et al*., 2011), and considering that the seed is rich in protein and energy it is often classified as “complete food” due to the high nutritional value of the crop (Afoakwa 2007, Ouedraogo 2012, Mayes *et al.*, 2019).

2.1.4 Economic importance of bambara groundnut

Bambara groundnut is ranked as the third most important legume in Africa in terms of production and consumption after groundnut (*Arachis hypogea* L.) and cowpea (*Vigna unguiculate*) (Gerrano *et al.*, 2016). The crop often serves as a commodity that generates income for the farmers and contributes to economic return improvement (Anchirinah, Yiridoe and Bennett-Lartey, 2001). As bambara groundnut is mostly cultivated by smallholder farmers, they are mostly restricted to local production and consumption and are sometimes processed by small scale entrepreneurs into flour, juice, snacks, and sold in local markets for income (Azam-Ali et al., 2001). The development of the crop will be expected to make an economic impact at both national and regional levels, as has been the case of Roselle (*Hibiscus sabdariffa*), and Okra (*Abelmoscus esculentus*) in Sub Sahara Africa, which has been established in global markets because of consumers interest, commercialisation, and marketing strategies contributing to the rediscovery of these valuable species (IPGRI, 1999).

2.1.5 Physiological characteristics of bambara groundnut

Bambara groundnut is characterised by nitrogen fixation through symbiotic activity with *Rhizobium* sp., which has been known to improve soil fertility and beneficial to cereal crops when intercropped (Ncube *et al*., 2007). Furthermore, several studies have referred to bambara groundnut as a drought-tolerant plant (Collinson *et al.*, 1997; Muhammad *et al*., 2016) that can be cultivated in drought-prone areas. Achieving drought tolerance in plants is achieved through three mechanisms: escape, tolerance, and avoidance (Turner *et al*., 2001). Bambara groundnut is classified as a drought-tolerant plant because it possesses the avoidance and escape mechanisms hence, its reaction to low precipitation or drought conditions (Turner, Wright, and Siddique, 2001; López-Blanco *et al.*, 2018). During drought conditions, bambara groundnut maintains its water status through stomatal regulation, reduction in leaf area index (LAI), and osmotic adjustment(Collinson *et al.*, 1997).

The significant effect of high temperature and low precipitation can occur at different stages of development and growth of bambara groundnut, especially during the germination and reproductive stages (Collinson *et al.*, 1997; Mabhaudhi *et al.*, 2018). For the temperature condition best suited for the cultivation of the crop, Nordin and Singh (2015) reports that under an average temperature of 20-35^{o}C, bambara groundnut grows well, but an increase in temperature to about 40^{o}C will result in a reduction in growth. Furthermore, Bamshaiye *et al*., (2011) argues that although the crop requires a warm temperature, the ideal average temperature suitable for the development of the crop is 20-28^{o}C with an optimum of 30-35^{o}C for seed germination, and maintains that temperatures above these ranges could cause the crop leaves to die, resulting to reduction in crop yield.

2.1.6 Need for bambara groundnut

The over-reliance of the food system on a handful of major staple crops is becoming inherently unsustainable with agronomic, nutritional, economic, and ecological risk (Ebert, 2014). Also, the production level of the staple food crops can no longer meet the sufficient projected food demand and requirements (Gressel, 2008). Thus, meeting the growing food demand should not only rely on a few staple crops. Hence, the need for crop diversification in the agricultural crop system which will help in the promotion of agro-biodiversity (Newton, Johnson, and Gregory, 2011), and can be undertaken through cereal-legume intercropping or rotation, which over the years have gotten little or no attention in southern Mali (Snapp *et al.*, 2010; Falconnier *et al.*, 2016).

2.2 Climate in West Africa

Three major global drivers determine the climate over West African. These global drivers include the West African Monsoon (WAM), the Inter-Tropical Convergence Zone (ITCZ), and El Nino Southern Oscillation (ENSO). The West African Monsoon (WAM) controls the rainfall pattern over West Africa, and is produced by the reversal heating of ocean and land dictating the seasonal rainfall pattern in West Africa (Nicholson, 2013). Also, the WAM is the primary source of moisture with impacts on rainfall timing (onset/cessation), rainfall variability, and the high amount of annual rainfall over West Africa (Omotosho and Abiodun, 2007). According to Abiodun *et al.*, 2008, the WAM comprises of different atmospheric processes namely: the monsoon flow, the African Easterly Waves (AEW), Mesoscale Convective System (MCSs), the African Easterly Jets (AEJs) and Tropical Easterly Jets (TEJs). The interaction of the aforementioned processes enhanced by the supply of moisture from the monsoon flow results in a summer monsoon rainfall in West Africa (Janicot *et al.*, 2011).

The Inter-Tropical Convergence Zone (ITCZ) is a surface feature defined by air mass convergence (Nicholson, 2008). It is the position over the ocean where the two major air masses meet (Abiodun *et al.*, 2008).

2.2.1 Climate in Mali

Mali is a Sahelian landlocked country in West Africa and home to West Africa's largest inner Niger delta (an area of lakes, fluvial wetlands, and floodplains in the semi-arid Sahel area of central Mali) of River Niger (Mahe *et al.*, 2011). The movement of the tropical rain belt ITCZ and the WAM influences the seasonal rainfall in the country. The country has three seasons: the wet season, which starts from June to September/October, the cool dry season from October to January, which comes with Harmattan wind, and the hot dry season from February to May, during which temperature is around 33^{o}C.

2.2.2 Classification of Mali agroecological zones

The classification of the Agroecological zones in Mali is as follows: Saharan, Sahelian, Sudanese, and North Guinea climate (Figure 2.2). The Saharan zone is situated in the north of Mali, occupies two-thirds of the country, with an annual average rainfall ranging from 50 to 250mm. The Sahelian zone forms a transitional zone between the Saharan and Sudanese zones with an annual average rainfall ranging from 250 to 500mm. The Sudanese zone located in the south of the Sahelian zone and has an annual average rainfall of 500-800mm. The North Guinea zone covers the south of the country with an average annual rainfall of >1000mm (Bertrand and Gigou, 2000).

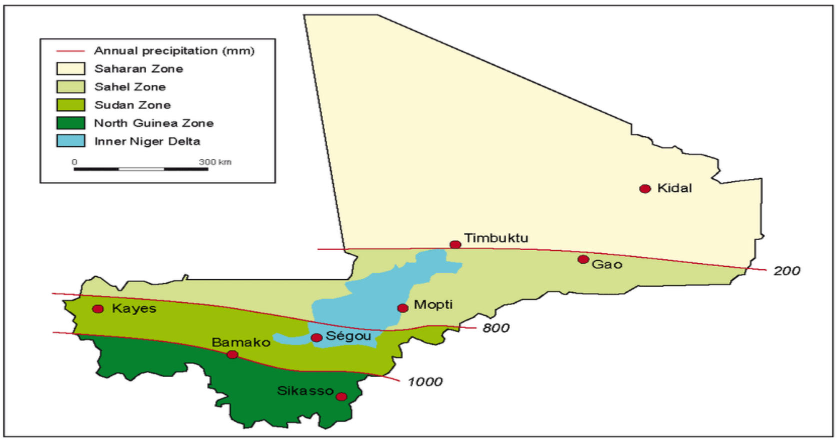

Figure 2.2: The annual average rainfall and agroecological zones in Mali.

2.2.3 Climate system classification in Mali

German botanist-climatologist Waldimir Köppen developed the Köppen climate classification system, based on precipitation, temperature, and natural vegetation. The Köppen climate system classification grouped the West Africa climate into two climatic zones, namely: dry, and tropical climatic zones. The dry climatic zone comprises of: The Hot Desert (BWh) and the Hot Summer Arid (BSh) climates, while the tropical climatic zone consists of: The Tropical Forest Climate (Am), Tropical wet-dry Climate (Aw), and the Tropical Monsoon Climate (Am). The three climate zones found over Mali are the Hot semi-Arid (BSh), Hot Desert (BWh), and the Tropical wet-dry (Aw) climatic zones.

The tropical wet-dry (Aw) in blue (Figure 2.3) covers the lower area of Mali and is dominated by an extended dry season during winter, and wet season with precipitations usually under

1000mm and less than 60mm in the driest months. The mean annual temperature in the zone records about 26°C and diurnal temperature range of 1.7-2.8°C.

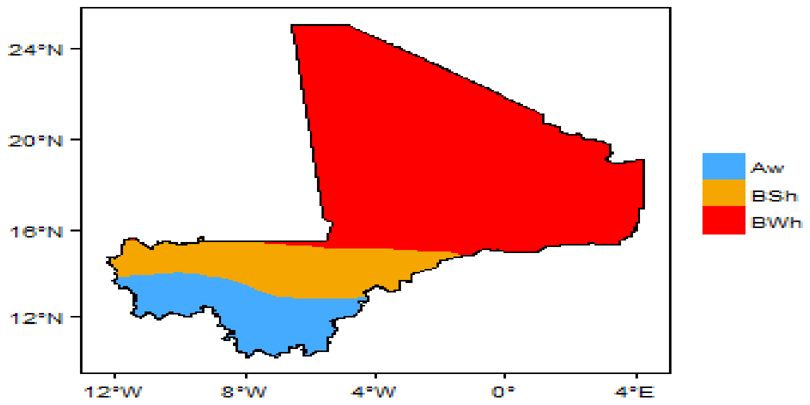

Figure 2.3: The Köppen climate classification over Mali.

The hot desert climate (BWh) covers the upper area of Mali indicated in red (Figure 2.3). Precipitation in this area is less than 50%, irregular and unreliable as a result of the area's dryness and low relative humidity. BWh has the highest sunshine hours per day when compared to earlier mentioned climate types. Also, the annual temperature is above 10°C, with a mean monthly temperature of 30°C, a diurnal temperature range of 5.6-8.3°C.

The warm semi-arid climate (BSh) indicated in orange (Figure 2.3) covers the central area of Mali, in this climate zone, the mean precipitation is less than the BWh. The annual rainfall is between 250mm–500mm, exceeding that of BWh. The highest temperature in the zone is about 58°C, with an average temperature above 18°C. Notably, the major controlling factor of BWh and BSh is the dominating subtropical high-pressure system throughout the year, leading to the cloudless skies during the day and low temperature at night (FAO,1985).

2.3 Representative Concentration Pathway (RCP)

The Representative Concentration Pathway (RCP) was developed using Integrated Assessment Models (IAMs) (Moss *et al.*, 2010) to understand the interaction between the climate system and possible future evolution of the atmospheric composition. The RCPs are used to drive climate model simulations. They were developed based on simulation from a set of IAMs that provide the concentration of radiatively important GHGs, several aerosols together with land-use change that are consistent with a set of climate outcomes used by the climate modelling community (Arora *et al.*, 2011). However, Meinshausen *et al.* (2011) argue that due to the development of the RCPs from four different IAMs, there could be some inconsistencies in the relationship between emission and concentration in the interpretation of climate consequences of the RCPs. There exist four RCPs covering the 1850-2100 period, each corresponding to a specific radiative forcing level: the RCP 2.6, a stringent mitigation scenario, two intermediate scenarios 4.5, 6.0, and 8.5W/m^2 the scenario with very high GHG emission.

2.4 Climate change trends and projections

An understanding of past climate trends and projections will help in assessing the impact of climate change on agricultural crops as well as in identifying countries and regions that will be most affected, to suggest adaptation and mitigation measures. Multiple studies have projected different degrees of change in average temperature and precipitation using different time periods, RCPs, and climate models (Sylla *et al.*, 2010, 2015; Mounkaila, Abiodun, and Bayo Omotosho, 2015; Barry *et al.*, 2018). However, from the studies, there is a consensus of uncertainties in the future climate conditions over Africa. For instance, while East Africa is likely to experience a wetter period due to a projected increase in precipitation, and precipitation in West Africa is expected to become less predictable (Kotir,2011). In addition, Coop (2008) predicts a pattern consistent with an increase in temperature though at varying degrees, and a trend of drier winter precipitation in Southern Africa, wetter period in east Africa and a high level of uncertainty in west Africa.

By the 21st century, temperature increase over West Africa is expected to increase faster than the increase in mean global temperature with projected climate departure occurring one to two decades earlier than the global average (Mora *et al.*, 2013). The future climate projection over west Africa has indicated an increase in temperature between 1.1 and 4.8^{o}C, with variations in precipitation (IPCC, 2013), as an increase in the annual temperature trend has been observed over west Africa, particularly in Burkina Faso and Mali (Barry *et al.*, 2018). Furthermore, Neumann *et al.* (2007) predict a substantial decrease in mean annual precipitation and delayed onset of the rainy season over some regions in West Africa. Furthermore, in west Africa due to the changes in ecological conditions, there has been a recorded southward shift of climate zones resulting in the spread of the Sahara desert into the Sahelian zone, as in the case of Mali causing desertification (Wittig *et al.*, 2007).

2.4.1 Climate projections in Mali

Over the years, Mali has experienced changes in precipitation, manifesting as irregularities in precipitation, and delay in the onset of the rainy season according to Mali Direction Nationale de la Meteorologie (DNM) and has resulted in a hotter and drier climate in the country. However, Funk *et al*. (2012) argue that there has been a rainfall recovery since the mid-1980s based on the study using 1900-2009 rainfall data extracted for crop growing regions in southwestern (Kayes and Koulikoro) and southeastern (Mopti, Ségou, and Sikasso) Mali.

Based on MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change)/SCENGEN (Regional Climate Scenario Generator) projections, (Ebi *et al.*, 2011) predicts that alongside a trend of uncertainty in rainfall, the average temperature across Mali is expected to increase by approximately 1^{o}C by the 2030s and 2-3^{o}C by the 2060s, when compared to a baseline (1990). While under RCP 4.5 and 8.5, the annual maximum and minimum temperatures of southern Mali are predicted to increase by 2.9 and 3.3^{o}C by the mid-century (2040-2069) when compared with the baseline (1980-2009) (Traore *et al.*, 2017). Funk *et al*. (2012) also predict a reduction in precipitation and an increase in temperature in southern Mali from 2010-2039, based on observed data from 1960-2009. As the temperature continues to get warmer and precipitation patterns remain uncertain crop suitability, growth, and yield are at risk of being highly affected (Schlenker and Lobell 2010; Knox *et al.* 2012). In addition, these projections remain a significant threat to the rain-fed agricultural farming system in Mali, mainly as about 90% of the crop production depends on this system (Rosegrant, Cai, and Cline, 2002).

2.5 Impact of climate change on crops

Temperature and precipitation are crucial in crop production, as crop growth and crop yield respond to the changes in these climate variables simultaneously (Hoffman, Kemanian, and Forest, 2018). The changes in these two variables pose a significant risk to crop production, especially in the 21st century. There exist a consensus of several in-depth studies, of a significant adverse effect of extreme weather events such as drought and high temperature on agricultural crops (Lobell, Schlenker and Costa-Roberts, 2011; Teixeira *et al.*, 2013; Eyshi Rezaei *et al.*, 2015; Urban *et al.*, 2015; Ahmed *et al.*, 2018; Gondim *et al.*, 2018; Zhu *et al.*, 2018). In Africa, climate change is projected to increase occurrence of erratic rainfall, increase drought, and warming temperature which could result in shortened growing seasons of crops as well as reduction of crop suitability and yield (Berg *et al.*, 2013; Müller et al., 2011; Olsson et al., 2014; Porter et al., 2014). Furthermore, Bocchiola, Nana, and Soncini (2013), suggest that by 2085 if global warming exceeds 1.5-2.5^{o}C in Africa, about 25-42% of the plant species in the area would be endangered with the possibility of losing 90% of these species to extinction.

Over west Africa, crop yield loss in the Sudano-Sahelian countries is projected to be at an average yield loss of 18% compared to the 13% yield loss in the Southern Guinea Savannah countries due to the already drier and warmer climate in the Sudano-Sahelian (northerly) countries (Sultan *et al.*, 2013). Also, Dell, Jones, and Olken (2012) indicate that a 1^{o}C increase in temperature in developing countries such as Cameroun, Nigeria, Ghana, and Mali has contributed to a 2.66% decrease in agricultural output and resulted in an average of 1.3% economic growth reduction. In Sudan savanna and Guinea agroecological zones of Northern Ghana Armah *et al.* (2011) project that drier conditions as a result of increased temperature and reduced rainfall will result in 8% and 14% reduction in cropland suitable for sorghum and millet cultivation, respectively. Similarly, Antwi-Agyei *et al.* (2012) suggest that significant crops (such as millet, and sorghum, maize) are likely to have low production in the Northern, Upper East, and West areas of Ghana because of drought. In Cameroun with a projected annual temperature increase of 0.7-0.8^{o}C, 3.1-4.4^{o}C and a distinctive decreasing trend in precipitation in the 2020s and by the 2080s (Tingem *et al.*, 2008), maize yield is projected to experience 27.1 to 67.6% reduction as bambara groundnut yield is projected to increase in the range of 27.9 to 153.6% in the 2020s and 5.5 to 162% by the 2080s (Tingem and Rivington, 2009). Also, Tingem, Rinington, and Bellocchi (2009) suggest that an increase in temperature would be beneficial to bambara groundnut genotypes.

2.6 Crop modelling

The term model, according to Dejenie (2019), refers to "*a schematic representation of the idea of a system or an operation of imitation or a set of equations, in which it represents the overall behaviour of a system.*" Crop models refer to the tools that can be used to monitor, evaluate, understand, and predict crop growth, development (before sowing to maturity) and yield at a given time interval. They work with the integration of information on crop agro-climatology, ecophysiology, soil chemistry, and other related fields. They are used to simulate and determine the relationship between crop growth, development, suitability, and yield depending on environmental factors (such as solar radiation, drought, or warming temperature), socioeconomic factors (such as net income, market price, farm inputs or population), as well as soil moisture and nutrient conditions (Hodson and White, 2010). Crop models are also used for climate impact assessment studies, in diagnosing crop growth or yield gap problems, decision making, forecasting, adaptive management, and risk reduction (Challinor *et al.*, 2004). Furthermore, crop models have been widely used to investigate the relationship between climate and crop production using observed climate data as a boundary for driving the crop model (Osborne *et al.*, 2007).

Since the development of crop models in the 1980s, there has been an evolution in the design and development of the models due to recent advancements in technology (Jones et al., 2017). These recent technological advancements have created opportunities for the consideration of factors such as pests and diseases, soil, climate system, and crop phenology amongst others in making projections depending on the conditions considered for simulation (Hoogenboom, 2000; Greenwald *et al.*, 2006; Confalonieri *et al.*, 2013). There is a gap in the use of crop models to study the impact of climate change on underutilised crops, while different types of crop models have been designed and used on staple crops such as rice, millet, maize, wheat, sugarcane, and soybean. Few of these models either have the ability or been applied in the simulation of underutilised crops, this can be attributed to lack of balance in calibration and representativity of the models.

There are two main crop modelling approaches commonly used in simulating the impact of climate change on a crop, they are the process-based and empirical crop modelling approaches.

2.6.1 Process-based crop modelling

Process-based crop models are designed to simulate crop response to different environmental conditions at different timescales across a given spatial scale, relatively on a larger scale and are the most commonly used models for climate change impact assessment on crop production. The process-based crop model provides a physiological mechanism for climate and crop production outcomes (Roberts *et al.*, 2017), achieved by computing crop dynamics based on deterministic equations and simulations of underlying processes at time scales of minutes to days (Tubiello and Ewert, 2002). They enable the understanding of the agronomic adaptation techniques while providing an understanding of crop growth and the interaction between crop, soil, and climate (Lobell and Asseng, 2017).

One weaknesses of process-based crop models is its usage at a large spatial scale, despite been designed for a homogenous scale where there is a finer resolution for parameter demands (Challinor *et al.*, 2004; Abraha and Savage, 2006). Furthermore, Roudier *et al.* (2011) indicate that at a large spatial scale process-based crop model does not capture the level of details or provide adequate information on climate impacts found at the farm scale. However, there are efforts by the Agricultural Model Intercomparison and Improvement Project (AgMIP) to further develop the models with the ability to simulate on a global scale (Rosenzweig *et al.*, 2013). Another weakness of the process-based crop models is its limitation to the biophysical processes in which the development is based. For instance, models developed based on nitrogen-use or water-use efficiency, radiation-use efficiency (RUE), the effect of CO_2, or the impact of different agronomic management practices such as irrigation or mulching (Challinor *et al.*, 2009).

Some examples of process-based crop models include the widely used Decision Support System for Agro-Technology Transfer (DSSAT) (Thorp *et al.*, 2008; Liu *et al.*, 2011; Abera *et al.*, 2018), Agricultural Production Systems Simulator (APSIM) (Traore *et al.*, 2017; Brown *et al.*, 2018; Zhu *et al.*, 2018), AquaCrop (Kløve *et al.*, 2014; Karunaratne *et al*., 2015; Mabhaudhi *et al.*, 2018), Environmental Policy Integrated Model(EPIC) (Brown *et al.*, 2018), Crop Environment Resource Synthesis-Mazie (CERES-Mazie) (Lobell and Burke, 2010), SOYGRO-soybean (singh *et al.,* 2010), and CANEGRO-sugarcane (Singels and Bezuidenhout, 2002; van der Laan *et al.*, 2011). Multiple studies in West Africa have used different process-based crop models to simulate and make projections of climate change impact on crops (Tingem *et al*., 2009; Hoffman *et al*., 2018).

2.6.2 Empirical crop modelling

Empirical crop models (non-dynamic regression) are developed based on the idea of making future predictions using observed relationships. These crop models are developed using historical climate and crop yield data to form a relatively simple regression (Lobell and Burke, 2010). The empirical crop models applied are alongside future climatic projections to assess the impact of climate change and are relatively suited for multi-season and inter-annual variability analysis at regional production (Hertel and Rosch, 2010).

The three main bases of the empirical crop models include: (1) it is based on time-series data from a one area or points with the advantage of capturing the behaviour at a given time, (2) it is based on changes in time and space assuming common parameter values of all locations, and (3) it is based solely on changes in space, particularly prone to errors from omitted variables (Lobell and Burke, 2010). The empirical crop models have different strengths and weaknesses. For instance, although some empirical crop models make use of experimental field calibrated data, the critical strength of the models is that they have limited use and reliance on these field calibrated data; as they can also use observational data. The benefit of using observational data is that it takes into account a farmer's management behaviour even when is not implicitly observed (Roberts *et al.*, 2017).

A weakness of an empirical crop model, according to White *et al.* (2011), is the reliability of the models on prediction of future responses solely based on past conditions rather than causes and effects. As the models do not account for plant physiological and biophysical processes that highlight the interaction between factors like climatic conditions, soil, pests and diseases, and agronomic management practices. Another weakness of the empirical crop models is the problem of co-linearity between the predictor variable (e.g. temperature and precipitation), assumption of stationarity (e.g. that past relationship will hold in the future, even if management system evolves), and low signal-noise ratios in yield or weather records in some locations (Lobell and Burke, 2010). An example of co-linearity was shown in a study by Lobell and Ortiz-Monasterio, (2007) of wheat yield in Mexico, indicating a historical correlation between minimum temperature (T_{Min}) and the wheat yield as a result of negative correlation between T_{Min} and solar radiation. Also, using quadratic equations Peng *et al*., (2004), showed the association between yield and minimum temperature in Philippine rice yield, suggesting that with 1^{o}C increase in T_{Min} there is a 10% decrease in rice yield and with a 1^{o}C variable in average temperature, there is 15% decrease in rice yield in Philippine. However, Sheehy, Mitchell, and Ferrer (2006) highlighted a co-linearity problem in the Peng *et al*., (2004) study, arguing that solar radiation was a robust negative correlate of T_{Min}, hence an apparent negative effect of warming could quickly arise from a positive impact of higher solar radiation especially when trying to predict the range of historical variation.

Examples of empirical models include the Ecocrop model (Jarvis *et al.*, 2012; Egbebiyi *et al.*, 2019; Hunter and Crespo, 2019), MaxEnt (Merow, Smith, and Silander, 2013), and CLIMEX

(Kriticos *et al.*, 2012, 2015; Ramirez-Cabral, Kumar, and Shabani, 2017). Over the past years, multiple empirical crop models have been developed and used for climate impact assessment (Welch *et al.*, 2010; Ramirez-Villegas, Jarvis, and Läderach, 2013; Palazzoli *et al.*, 2015; Shi *et al.*, 2018).

2.6.3 Climate change impact assessment using the crop model

Crop model often linked with climate models for impact assessment studies, climate models allow for the understanding of the heterogeneity of future climate while providing insight into future climatology expected in any region. Hence, with the combination of crop and climate models, it is possible to model and estimate the short and long-term impacts of climate change on crops. With the growing concerns around climate change and its significant effect on crops, the linking of crop models and climate model scenarios to assess the response of crops to climate change can provide the information required by farmers and policymakers for strategic decision making. The combination of crop models and climate models can be applied to both global and regional spatial scales. However, for decision making impact assessment studies using crop models have been projected to be better at the regional spatial scale (Fischer *et al.*, 2005).

Several crop simulation studies have examined changes in crop production within the past, present, and future periods using a combination of General Climate Models (GCMs) and crop models. For instance, modelling the suitability of maize production to climate change, using CLIMEX distribution model and two GCMs (CSIRO-Mk3.0 and MIROC-H) under A2 emission scenarios for 2050 and 2100, Ramirez-Cabral *et al*., (2017) projects a decrease in maize suitability over Africa, as a result of an increase in temperature and low rainfall. In addition, changes in climate are projected to likely influence the effect of pests and diseases on crops (Jaramillo *et al.*, 2011; Serge .S *et al.*, 2011; R. Yáñez-López *et al.*, 2012). These changes have prompted the growing interest in the use of crop models to assess the influence or effect of pests and diseases on crops, despite crop models rarely having the ability to model or forecast these to climate change. Nevertheless, using the SimCast model (a model that predicts the effect of weather on potato late blight), Sparks *et al.* (2014) estimates a likely increase in the global potato late blight disease incidences under a warming temperature; however, early planting in cooler seasons would result in optimal productivity and reduce the disease risk.

Also, Lane and Jarvis (2010) investigated the impact of climate change on suitable areas for chickpea, wheat, pearl millet, and soybean production and projects a 2.6% decrease in the land area suitable for planting of the crops in Sub Saharan Africa. Sonder, Okonkwo, and Asiedu (2010), using 18 GCMs and FAO-Ecocrop model, predicts a 10% increase in yam spatial suitability in Northern Nigeria from 2040-2069 when compared to the 1951-2000 period. Other crop suitability modelling studies carried out across different countries in West Africa include Guinea-Bissau (Le Page *et al.*, 2017), Mali (Badini and Dioni, 2001; Sogoba *et al.*, 2007; Boken *et al.*, 2008; Conijin *et al.*, 2011), Senegal (Oettli *et al.*, 2011), and table 2.2.

Table 2.2: Reviewed crop-climate impact studies in West Africa

No	Title	Author(s)	Crops	Year of Publication	Region	Number of GCM	Crop model
1	Improvement of spatial modelling of crop suitability using a new digital soil map of Tanzania	Kristin Piikki Leigh Winowiecki Tor-Gunnar Vågen Julian Ramirez-Villegas Mats Söderström	Common Beans	2017	Tanzania	32	Ecocrop
3	Mapping maize yield variability in Mali	Conijin, J.G, Hengsdijk, H, Rustgers, R Jongschaap, R.E.E	Maize	2011	Mali	GCMs + CRU	Linear Interpolation of Utilisation of Light (LINTUL)
4	Monitoring peanut contamination in Mali (Africa) using AVHRR satellite data and a crop simulation model	Boken, V. K., Hoogenboom, G., Williams, J. H., Diarra, B., Dione, S., Easson, G. L.	Peanut	2008	Mali	AVHRR satellite data	CSM-CROPGRO-peanut model
5	Are our regional climate models relevant for crop yield prediction in West Africa?	Oettli, Pascal, Sultan, Benjamin, Baron,		2011	Senegal	9	SARRA-H

		Christian, Vrac, Mathieu					
6	Predicted changes in suitability and agro-climatic factors due to climate change for yam production in Nigeria	Sonder, K, Okonkwo, C.C, Asiedu, R	Yam	2010	Nigeria	18	Ecocrop
7	An operational approach to high-resolution agro-ecological zoning in West-Africa	Y. Le Page, Maria Vasconcelos, A. Palminha, I. Q. Melo, J. M. C. Pereira		2017	Guinea-Bissau	-	Ecocrop
8	A study to identify the suitable locations for the adaptation of underutilised tropical fruits tree species using GIS	C.Bowe	Tamarind, Ber, Jackfruit	2004	Niger, Mali, Nigeria, Senegal	-	-
9	Modelling cereals crops to assess future climate risk for family food self-sufficiency in southern Mali	Traore, B, Descheemaeker, K, van Wijk, M. T, Corbeels, M, Supit, I, Giler, K. E.	Maize Millet	2017	Mali	N'Tarla Metrolo gical	APSIM

						Station Data	
10	Assessing Future Spatio-Temporal Changes in Crop Suitability and Planting Season over West Africa: Using the Concept of Crop-Climate Departure	Temitope S. Egbebiyi, Chris Lennard, Olivier Crespo, Phillip Mukwenha, Shakirudeen Lawal and Kwesi Quagraine	Cassava Maize Groundnut Plantain Pearl Millet Sorghum	2019	West Africa	GCMs	Ecocrop

Chapter 3: Data and methodology

This chapter describes the study area Sikasso and Ségou regions in southern Mali, West Africa (hereafter referred to as Sikasso and Ségou), the crop and climate datasets used in the study. It also contains the description of the crop model (Ecocrop) used for simulation of suitability. Furthermore, this chapter describes the approaches applied in the simulation of the seasonal and spatial suitability of bambara groundnut under the past (baseline and historical) and future (near term and end of century) time periods.

3.1 Study area

Mali is one of the least developed countries in West Africa[3], and is strongly dependent on rain-fed agriculture. The major crops cultivated in Mali include pearl millet, rice, maize, sorghum, cotton, and sugarcane, while the minor crops grown in the country include cassava, cowpea, shea nut, a variety of vegetables (e.g. tomatoes, bell and chili pepper, lettuces) and the neglected and underutilised crops found in the country include fonio and bambara groundnut. Bambara groundnut accounts for 4% of legume production in Mali (Ministere de l'Agriculture, 2016).

3.1.1 Sikasso and Ségou regions

Sikasso (11.3°N, 5.6°W) and Ségou (13.8°N, 6.0°W) regions (Figure 3.1) are situated in southern Mali, considered as the central agricultural hub of Mali, and a substantial amount of the country's food comes from these regions. The regions are located within the Sudano-Sahelian zone of West Africa and are characterised by a sub-humid climate regime with semi-arid in Sikasso and arid in Ségou. The aridity of Ségou is becoming more obvious owing to a reduction in the mean annual precipitation over the region (World Bank, 2012); however, the climate projection results of this study suggest an increase in precipitation over the region. The average temperature in Sikasso ranges from 27^{o}C to 33^{o}C in Ségou, and annual total precipitation ranges from 250 to 1100 mm. Ségou region, situated in the Sahel agro-ecological zone (AEZ), receives annual precipitation of 250-550 mm while the Sikasso region located in the Sudan AEZ receives mean yearly precipitation of 550-1100 mm. The regions are

[3] https://unctad.org/en/Pages/ALDC/Landlocked%20Developing%20Countries/LLDCs-Map.aspx

characterised by a uni-modal rainy season, which extends from April to October, with a peak in July/August.

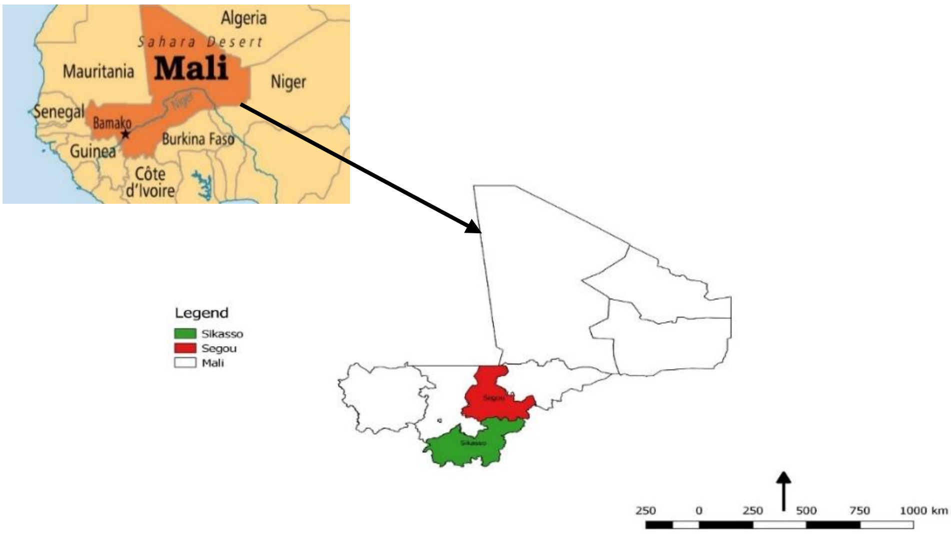

Figure 3.1: Sikasso (green) and Ségou (red) regions in Mali, West Africa.

3.2 Sources of data

This study used four different datasets: (1) climate observation datasets from the Climate Research Unit (CRU), (2) 10 climate model simulation, (3) bambara groundnut ecological threshold dataset, and (4) bambara groundnut crop yield dataset.

3.2.1 Climate Research Unit (CRU) data

The CRU dataset is a gridded observational monthly climate data series from the Climate Research Unit of the University of East Anglia (CRU TS 4.01)[4] provided at 0.5° x 0.5° resolution within the period of 1901-2016 (Harris *et al.*, 2014). The data contains monthly climate variables: precipitation, mean and minimum temperature. Several studies have employed the CRU observation data as reference data for various climate impact assessment studies (Preechamart *et al.*, 2018; Egbebiyi *et al.*, 2019)

3.2.2 Coordinated Regional Downscaling Experiment (CORDEX)

CORDEX is a program formed by the World Climate Research Programme (WCRP) to develop and evaluate experiments for the downscaling of global climate models to regional scales

[4] http://www.cru.uea.ac.uk

(e.g., CORDEX-Africa). Rossby Centre Regional Atmospheric model (hereafter RCA4) was used to dynamically downscale the 10 CMIP5 GCMs used in the study (Table 3.1)(Jones, Samuelsson and Kjellstr¨om, 2011) under a high-end GHGs emission scenario - the Representative Concentration Pathway (RCP) 8.5. The RCP8.5 represents a high concentration pathway and grows linearly during the 21st century with high radiative forcing values which is a reason for its selection for use in this study. RCA4 is one of the Coordinated Regional Downscaling Experiment (CORDEX) Regional Climate Models (RCM)(Giorgi *et al.*, 2009). The CORDEX data resulting from set of CORDEX models used in the study contains the 1951-2099 period at a 50km horizontal grid resolution (0.44^o x 0.44^o) and has been applied for various impact and adaptation assessment studies in different countries in West Africa (Nikulin *et al.*, 2012; Gbobaniyi *et al.*, 2014; Klutse *et al.*, 2016; Abiodun *et al.*, 2017; Kisembe *et al.*, 2018; Egbebiyi *et al.*, 2019).

Table 3.1: List of the dynamically downscaled CMIP5 GCMs used in the study

Modelling Centre	Institution Abbreviation	Model Name	Resolution
Canadian Centre for climate modelling and analysis	CCCMA	CanESM2	2.8^o x 2.8^o
Institute Pierre-Simon Laplace	IPSL	IPSL-CM5A-MR	1.25^o x 1.25^o
Norwegian climate center	NCC	NorESM1-M	2.5^o x 1.9^o
EC-EARTH consortium	EC-EARTH	ICHEC	1.25^o x 1.25^o
Commonwealth Scientific and Industrial Research Organisation in collaboration with the Queensland Climate Change Centre of Excellence	CSIRO-QCCCE	CSIRO_MK3.5	1.875^o x 1.875^o
NOAA geophysical fluid dynamics laboratory	NOAA GDFL	GFDL_ESM2M	2.5^o x 2.0^o
Atmosphere and Ocean Research Institute (University of Tokyo), National Institute for Environmental studies and	MIROC	MIROC5	1.4^o x 1.4^o

Japan Agency for Marine-Earth Science and Technology			
UK Met Office Hadley center	MOHC	HadGEM2-ES	1.9 ° x 1.3 °
Max Planck Institute for meteorology	MPI	MPI-ESM-LR	1.9 ° x 1.9 °
Centre National de Recherches Meteorolo-Giques/Centre Europeen de Recherche et Formation Avanceesencalcul scientifiqu	CNRMCERFACS	CNRM-CM5	1.4 ° x 1.4 °

3.2.2.2 Selection of time period

A 30-year time period was selected from the CRU and CORDEX climate data. The choice of the 30-year time period was made to highlight the suitability of bambara groundnut at a wide range year. For the past climate suitability simulation, one time period (1975-2005) was chosen from the CRU and CORDEX data, hereafter referred to as baseline (CRU) and historical (CORDEX) time period, respectively. The baseline period was used as a reference point to establish a relationship between the CRU simulated- and the CORDEX simulated- past climate suitability, to establish confidence in the use of CORDEX data for future climate suitability projections. For the future climate suitability projections, two time periods (2011-2040 and 2070-2099) were chosen from the CORDEX data, hereafter referred to as near-term and end of century time periods, respectively. The two future time periods were chosen to better understand the crop suitability at separate time periods in the future as change in climate conditions continue to occur.

3.3 Model description

The assessment of crop suitability is becoming a significant approach for determining the type of crop that is most appropriate to the conditions of a given area (Jarvis *et al.*, 2012; Piikki and Winowiecki, 2017). This approach often considers different environmental factors such as climate, water availability, and soil. Recently, several studies have used different environmental factors in assessing the suitability of a crop. For instance, climate variables (temperature and precipitation) (Sonder, Okonkwo and Asiedu, 2010; Egbebiyi, Crespo and

Lennard, 2019; Hunter and Crespo, 2019), and the combination of climate and soil characteristics information (AbdelRahman, Natarajan and Hegde, 2016).

3.3.1 Ecocrop model

The Ecocrop suitability model is an empirical model originally developed by (Hijmans *et al.*, 2001), based on the Food and Agriculture Organization (FAO)-Ecocrop database (Ecocorp, 2010). The model is designed to use climate ranges to determine the niche and distribution of a crop on a monthly scale basis and produce a suitability index range based on the interaction of the environmental variables (Hijmans *et al.*, 2001; Ramirez-Villegas *et al*., 2013). The model can serve as a tool for crop suitability assessments with the potential to inform strategic spatial, seasonal, and temporal planning for crop production. The choice of the Ecocrop suitability crop model for this study is based on its ability to produce spatially explicit suitability simulations of a crop. The Ecocrop model has been implemented in crop suitability projections of several crops such as sugarcane (Zabel, Putzenlechner and Mauser, 2014), Ryegrass, Alfalfa and Sorghum (Kim *et al.,* 2018) at a global scale. Sorghum, and common bean in Africa (Ramirez-Villegas *et al*., 2013; Ramirez-Cabral *et al*., 2017) and West Africa (Egbebiyi *et al.*, 2019), cassava in Africa (Jarvis *et al.*, 2012), Yam in Nigeria (Sonder, Okonkwo and Asiedu, 2010), *Kigelia africana* in Benin (Guidigan *et al.*, 2018a).

The Ecocrop model considers two ecological ranges (temperature and precipitation) for any given crop, with each defined by a pair of parameters for each of the variables, often known as the ecological threshold. These thresholds differ among crop species and are defined in the FAO-Ecocrop database. Table 3.2 shows the bambara groundnut ecological threshold as per the FAO-Ecocrop database and obtained from the "dismo" package in cran R software[5]. The suitability of a crop is determined using these thresholds (Ramirez-Villegas et al., 2013).

[5] https://cran.r-project.org/web/packages/dismo/index.html

Table 3.2: Bambara groundnut ecological thresholds as obtained from the FAO-Ecocrop database

	Climate variable	Value
T_{kill}	Killing temperature	0
T_{MIN}	Minimum average temp. at which plant will cease to grow(°C)	16
Top_{MIN}	Minimum average temp. at which plant will grow optimally(°C)	19
Top_{MAX}	Maximum average temp. at which plant will grow optimally(°C)	30
T_{MAX}	Maximum average temp. at which plant will cease to grow(°C)	38
R_{MIN}	Minimum rainfall(mm) during the growing season	300
Rop_{MIN}	Optimal Minimum rainfall(mm) during the growing season	750
Rop_{Max}	Optimal Maximum rainfall(mm) during the growing season	1400
R_{MAX}	Maximum rainfall(mm) during the growing season	3000
Crop cycle	Growing Duration(days)	90-180

3.3.2 Crop suitability computation

The Ecocrop suitability model directly integrates crop and climate conditions at a monthly time scale, which allows for analysis with dedicated temporal, seasonal, and spatial lenses. Its low computing demand makes it particularly suited to compute crop suitability over vast areas and periods. Computing the suitability of a crop, the Ecocrop model performs two separate calculations using the two climate variables (temperature and precipitation) for each month as a possible start of the growing season (Hijmans *et al.*, 2001).

For this study, the suitability of bambara groundnut in Sikasso and Ségou was computed using the Ramirez-Villegas et al. (2013) procedure, which evaluates the adequate climatic conditions for temperature and precipitation within each month using the ecological thresholds and then calculates suitability from the resulting interaction between temperature and precipitation.

Temperature: Temperature suitability is computed using the minimum and mean temperatures for a growing season.

$$T_{SUIT} = \begin{cases} 0 & T_{MIN\text{-}Pi} < T_{KILL\text{ - }M} \\ 0 & T_{MEAN\text{-}Pi} < T_{MIN\text{- }C} \\ a_{T1} + m_{T1} * T_{MEAN\text{ -}Pi} & T_{MIN\text{- }C} \leq T_{MEAN - Pi} < T_{OPMIN - C} \\ 100 & T_{OPMIN - C} \leq T_{MEAN\text{-}Pi} < T_{OPMAX\text{ - }C} \\ a_{T2} + m_{T2} * T_{MEAN\text{ -}Pi} & T_{OPMAX - C} \leq T_{MEAN\text{-}Pi} < T_{MAX\text{-}C} \\ 1 & T_{MEAN\text{-}Pi} \geq T_{MAX\text{-}C} \end{cases}$$

Where T_{SUIT} is the temperature suitability index for the month *i*, $T_{MIN\text{-}C}$, $T_{OPMIN\text{-}C}$, $T_{OPMAX\text{-}C}$, and $T_{MAX\text{-}C}$ defined on a crop basis, a_{T1} and m_{T1} are the intercept and slope (respectively) of the regression curve between [$T_{MIN\text{-}C}$, *0*] and [$T_{OPMIN\text{-}C}$, *100*], a_{T2} and m_{T2} are the intercept and slope (respectively) of the regression curve between [$T_{OPMAX\text{-}C}$, *100*] and [$T_{MAX\text{-}C}$, *0*]. $T_{MIN\text{-}Pi}$ is the minimum temperature of the month *i*, $T_{MEAN\text{-}Pi}$ is the mean temperature of the month *i*, and T_{KILL} is the crop's killing temperature.

The model assumes that if the minimum temperature of the month in place is below [T_{KILL}], then the minimum absolute killing temperature will be reached in at least one day of the month, resulting in the crop failure. The final suitable temperature value (T_{SUIT}) is the minimum value of each month in the growing season.

Rainfall: The rainfall suitability computation as in temperature happens over a growing season, using the crop's growing season total rainfall as well as the minimum and maximum absolute and optimum ecological threshold.

$$R_{SUIT} = \begin{cases} 0 & R_{TOTAL\text{-}P} < R_{MIN\text{ - }C} \\ a_{R1} + m_{R1} * R_{TOTAL\text{-}P} & R_{MIN\text{- }C} \leq R_{TOTAL- P} < R_{OPMIN - C} \\ 100 & R_{OPMIN - C} \leq R_{TOTAL\text{-}P} < R_{OPMAX\text{ - }C} \\ a_{R2} + m_{R2} * R_{TOTAL\text{ -}P} & R_{OPMAX - C} \leq R_{OTAL\text{-}P} < R_{MAX\text{-}C} \\ 0 & T_{TOTAL\text{-}P} \geq R_{MAX\text{-}C} \end{cases}$$

Where R_{TOTAL} stands for the total rainfall for the crop's growing season, and R_{SUIT} stands for the rainfall suitability score. $R_{MIN\text{-}C}$, $R_{OPMIN\text{-}C}$, $R_{OPMAX\text{-}C}$, and $R_{MAX\text{-}C}$ defined on a crop basis, a_{R1} and m_{R1} are the intercepts, and the slope of the regression curve between [$R_{MIN\text{-}C}$, 0] and [$R_{OPMIN\text{-}C}$, 100], and a_{R2} and m_{R2} are the intercept and the slope of the regression curve between [$R_{OPMAX\text{-}C}$, 100] and [$R_{MAX\text{-}C}$, 0].

The total suitability index calculation involves the multiplication of the temperature (T_{SUIT}) and precipitation (R_{SUIT}) suitability index.

$$SUIT = T_{SUIT} * R_{SUIT}$$

Where – R_{SUIT} is the rainfall suitability index

T_{SUIT} is the Temperature suitability index

SUIT is the total monthly crop suitability index

A 12-month suitability output is generated, with each month showing the suitable index range for the crop.

3.3.3 Suitability indication

When the conditions over the growing season are beyond the absolute thresholds (white area, see Figure 3.2A), the suitability index is zero (not suitable), a state where the crop cannot grow under average conditions. When the conditions are between absolute and optimum thresholds (dark grey area, see Figure 3.2A), it shows a state where the crop can grow under a low range of suitable conditions. Furthermore, when they are within the optimum threshold with a suitability index of 1 (light grey area, see Figure 3.2A), it indicates a state where the crop can grow optimally under a high range of suitable conditions.

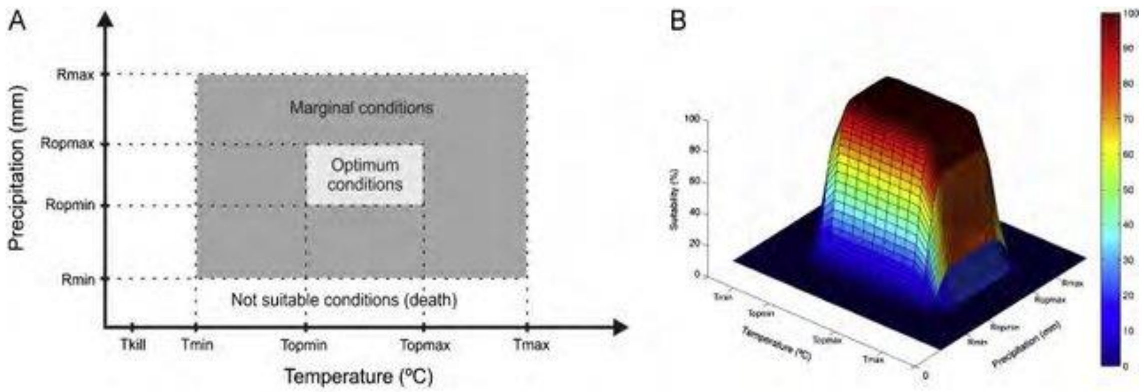

Figure 3.2: (A) Two dimensional and (B) Three-dimensional diagram of the Ecocrop model showing climate thresholds and crop suitability classification obtained from Ramirez-Villegas et al. (2013).

3.4 Simulating bambara groundnut suitability

For this study, the suitability assessment was analysed in two forms: seasonal and spatial suitability. The seasonal suitability focused on intra-annual variation describing changes within each month of the year, while the spatial suitability focused on shift, expansion, or reduction of suitable areas. Three impact metrics were generated for evaluating the response of the crop to future climate projections. The three-impact metrics include:

i. The seasonal suitability change considered the suitability of planting bambara groundnut within each month of the year in Sikasso and Segou, indicating where changes in seasonal climatology could result in a shift, reduction, or an increase in the planting months.
ii. The spatial suitability change considered the suitability in Sikasso and Ségou on a spatial scale by identifying areas where the variations in climatology could result in a high or low shift, expansion, or reduction in suitable areas.
iii. The final impact metric compares the changes in spatial suitability between the past and future time periods.

3.4.1 Identification and extraction of spatial resolution

To use the CORDEX data grid cells over Sikasso and Ségou regions for the suitability study, the grid cells were geo-referenced and overlaid using the Mali level 1 administrative boundary shapefile from Global Administrative Area (GADM) version 3.6[6]. After geo-referencing, the coordinates of the regions were obtained and used to mask and extract Sikasso and Ségou spatial layers. Raster spatial analysis was used in performing the geo-referencing and overlaying. The raster spatial analysis uses location and spatial relationships as an explanatory variable to extract features of data incorporated for statistical analysis (Martin and Bracken, 1991).

3.4.2 Computation of past and future climates

From the CRU and the 10 CORDEX datasets, the monthly climatology of the climate variables were calculated: mean temperature (T_{MEAN}), minimum temperature (T_{MIN}), and precipitation (prec) for the selected time period. From the CRU dataset, the 30-year mean computed was 1975-2005 (baseline). Furthermore, from the CORDEX datasets: the first 30-year mean calculated was 1975-2005 (historical), the second 30-year mean computed was 2040-2070 (near-term), and finally 2070-2099 (end of century) climate period. The computations generated an output of a mean 12-month climate value for each of the time periods and used to simulate the crop suitability model (Ecocrop).

[6]https://gadm.org/download_country_v3.html

3.5 Projected changes in temperature and precipitation

3.5.1 Monthly minimum and mean temperature

There was an agreement of an increase in minimum and mean temperature across all CORDEX monthly data through time and space across the time periods. Across the months, a consistent increase in both minimum and mean temperature was observed (Figure 3.3); however, the increase in minimum temperature was higher in June and July. For the mean temperature, the increase was higher in May and June. The changes in minimum temperature from historical to near term are expected to be approximatively $1.5^{o}C$ and about $5^{o}C$ historical to end of century. Also, the change in mean temperature from historical to near term is projected to be $2.5^{o}C$ and $4.5^{o}C$ from historical to end of century.

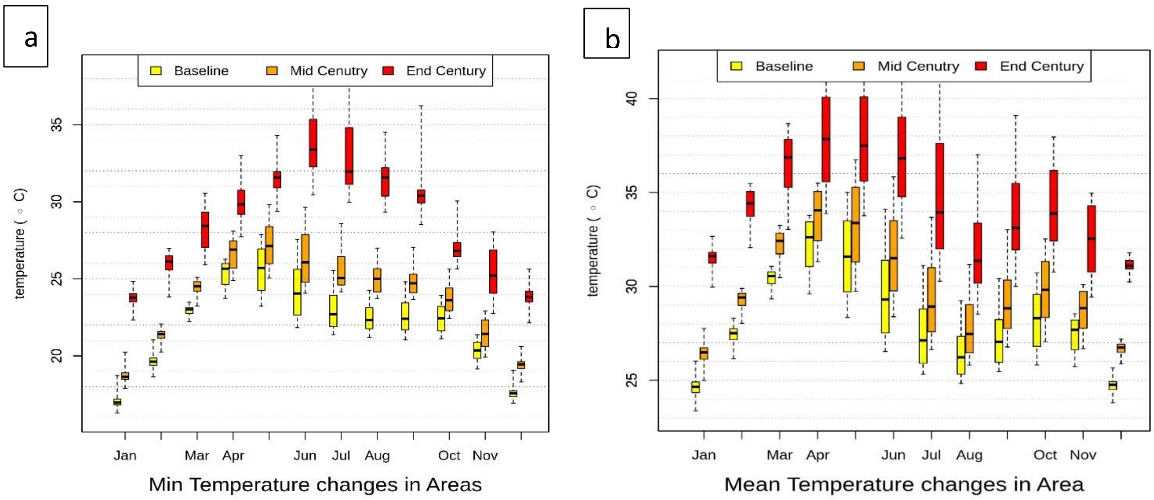

Figure 3.3: (a) Projected change in monthly minimum temperature(^{o}C), (b) monthly mean temperature(^{o}C) over Sikasso and Ségou for historical (1975-2005), near term (2011-2040) and end of century (2070-2099).

3.5.2 Monthly precipitation

CORDEX consistently projected a change in precipitation characterised by an increase in monthly precipitation, this intensified through time (Figure 3.4). However, April, May, and October showed an inconsistency in precipitation increase, indicating some uncertainty in precipitation in the regions. While there was a seasonal change in the projected monthly precipitation over the regions, there was also a marginal shift in the onset and cessation of the rainy season in the Sikasso and Ségou. Furthermore, the uni-modal precipitation regime of the regions was all well represented (Bertrand and Gigou, 2000; Funk *et al*., 2012). The regions could benefit from an increase in precipitation in the near term and end of century, especially at the end of century.

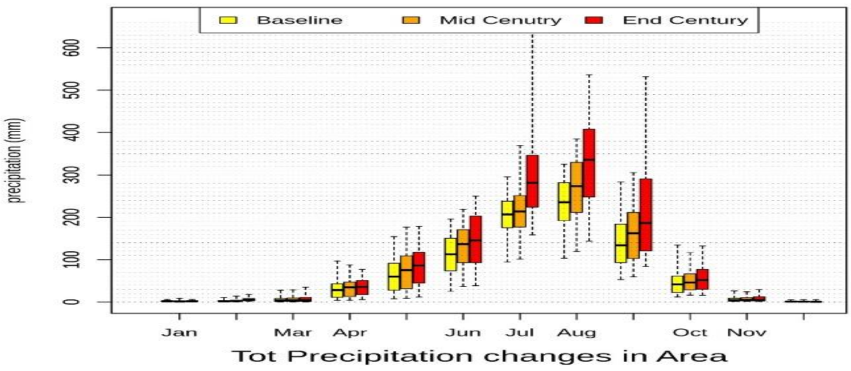

Figure 3.4: Projected monthly precipitation (mm) over Sikasso and Ségou for baseline (1975-2005), near term (2011-2040), and end of century (2070-2099).

The overall climate projections of Sikasso and Ségou show that the regions are expected to become warmer with a seasonal increase in precipitation, although not as obvious as the increase in temperature, despite some uncertainties in precipitation in the future. These observations concur with previous studies indicating a future increase in temperature and uncertainty in precipitation for Southern Mali and other parts of the country (Hulme *et al.*, 2001; Cooper *et al.*, 2008; Frappart *et al.*, 2009; Traore *et al.*, 2013; Diallo *et al.*, 2014).

3.5.3 Past and future suitability simulation

Using the 12-month climate values generated for each of the time periods as an input into the Ecocrop model, bambara groundnut suitability for Sikasso and Ségou was simulated under rain-fed conditions. This study did not perform any calibration of the ecological thresholds for the crop, instead it assumed the default Ecocrop ecological thresholds. Suitability simulation was performed for the past time periods, and suitability projections were also performed for each future time period. After the suitability simulation, the statistical function “summary” in R software[7] was applied to compute the minimum, maximum, mean, median, and first (25%)

[7]https://www.rdocumentation.org/packages/base/versions/3.6.1/topics/summary

and third (75%) quartile of suitability for each month over the regions. The best four suitable median months within the growing season were selected.

3.5.4 Estimation of past and future spatial suitability change

The change between the future and past spatial suitability of the crop was calculated at every grid within the cell. Computing for the changes, the future (near-term and end of century) spatial suitability was subtracted from the past (historical) spatial suitability, respectively and a map of relative change was generated.

3.5.5 Spatial suitability index for crop yield data years (2015-2017)

The capability of the model to simulate the spatial and seasonal suitability of the crop over Sikasso and Ségou was examined using the crop data years (2015-2017). The monthly climatology means for the three-year period was calculated by generating a mean 12-month climate value. The mean 12-month climate value was subsequently used as an input into the Ecocrop suitability model, to estimate the suitability index for the range of climate variables in the three years.

3.6 Representation of suitability

The simulation of the climatic suitability for every cell over an area allows for the representation of the seasonal and spatial suitability of the crop over the region. The representation of the spatial and seasonal suitability was done using a suitability index range and colour coded to match each of the suitability index ranges. The suitability index range for this study was categorised as follows (Table 3.3):

Table 3.3. Categories of the suitability index range

Suitability Index range	Description	Colour
0 - 0.1	Unsuitable	Grey
0.3 – 0.5	Marginal	Brown
0.5 – 0.7	Suitable	Yellow
0.7 – 0.9	Very suitable	Light green
0.9 - 1	Excellent	Dark green

3.6.1 Seasonal suitability representation

Figure 3.5 shows the distribution of seasonal suitability: the y-axis shows the percentage of the suitable area while the x-axis shows the 12 months in a growing season. Each of the months has a bar that contains different suitability index ranges.

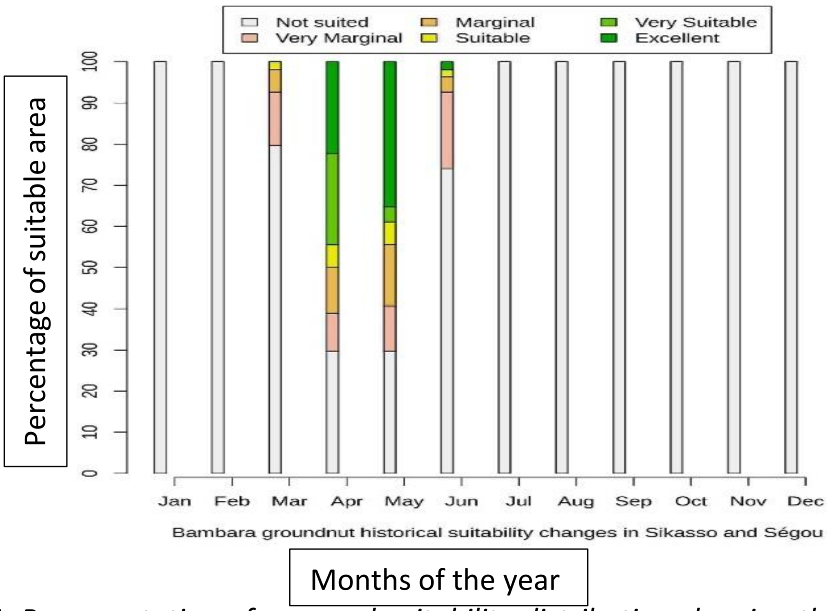

Figure 3.5: Representation of seasonal suitability distribution showing the months on the x-axis, and the percentage of suitable area in colour codes on the y-axis.

3.6.2 Spatial suitability representation

Figure 3.6 illustrates the representation of the spatial suitability index range distribution.

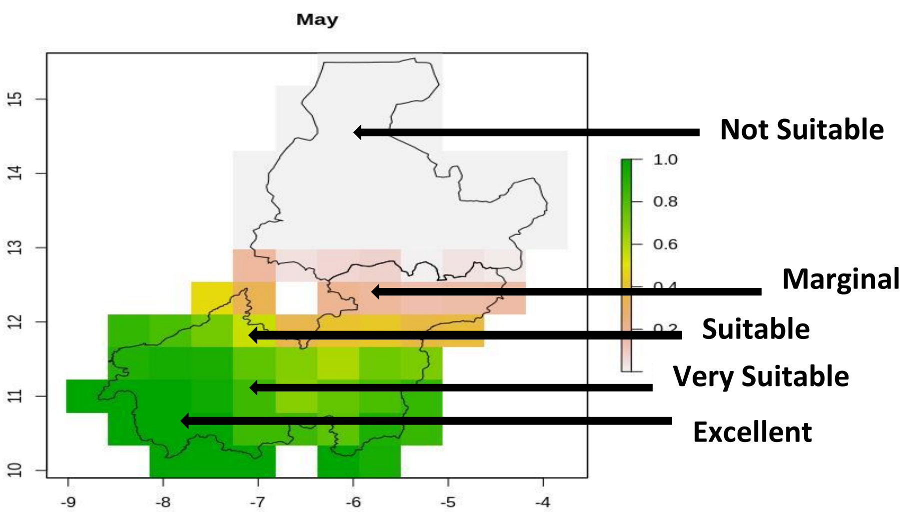

Figure 3.6: Representation of the spatial suitability distribution showing the colour code for the different suitability indexes.

3.7 Bambara groundnut yield data

Bambara groundnut yield data obtained from the Bioversity International project in collaboration with Institut d'Economie Rurale and the International Fund for Agricultural Development (IFAD PAPAM) programme were analysed in the study (see section 5.3). The data was generated from the cultivation of bambara groundnut in six communities (Figure 3.7) within Sikasso and Ségou over three growing seasons from 2015 to 2017.

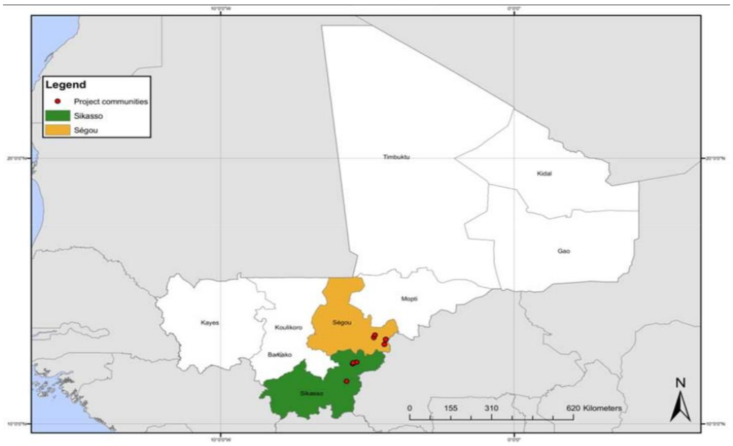

Figure 3.7: Map of Mali showing the experimental field project communities (red dots) where bambara groundnut cultivation occurred in Sikasso and Ségou (adopted from (Sidibe *et al.*, 2015)*.*

Chapter 4: Results

This chapter presents the seasonal and spatial suitability results from the simulations of bambara groundnut suitability of Sikasso and Ségou using the Ecocrop suitability model. It also describes the model validation for the historical period using the CRU observation dataset and ensemble of the 10 CORDEX, respectively. This chapter also shows the results of the seasonal and spatial suitability of bambara groundnut in the near-term (2011-2040) and by the end of century (2070-2099), as well as the projected changes in spatial suitability between the past and future time periods.

4.1 Model assessment

The relationship between the suitability of bambara groundnut under the baseline and historical time period (hereafter baseline and historical suitability), were evaluated using the baseline suitability as a reference point. This evaluation was performed to assess the performance of the crop model in simulating the past suitability of the crop to build confidence in future suitability projections.

4.1.1. Baseline and historical seasonal suitability

The simulated changes in baseline and historical seasonal suitability of bambara groundnut in Sikasso and Ségou showed in Figures 4.1 (a) and (b) consist of suitability index bars indicating the cumulative percentage of suitable area for each month in the two regions. The baseline and historical seasonal suitability indicate that the optimal dates suited for the planting of bambara groundnut in Sikasso and Ségou are between March to June, as other months showed no sign of suitability. The suitable months coincide with the onset of the rainy season within March to June.

Within the optimal planting dates (months), the baseline seasonal suitability indicates that the highest suitability index occurred in April and May, with 35 and 37% *excellent* suitable area, and 10 and 15% *very suitable* area for each month (Figure 4.1a). In March and June, while no area reached the *excellent* or *very suitable* suitability index, the months maintained its suitability despite being low, the cumulative percentage of suitable areas with suitability index ranging from *suitable* to *marginally suitable*.

The historical seasonal suitability (Figure 4.1b) shows that the optimal planting dates remain the same as in baseline seasonal suitability and further indicate that the months with the highest suitability remains April and May. However, there was a variation in suitability index, as while the cumulative percentage of an *excellent* suitable area in April was 25% and 35% in May, the *very suitable* areas in April was 15% and 10% in May. Also, in April and May, the percentage of *suitable* and *marginally suitable* areas increased. In March and June, the cumulative percentage of suitable area was low and ranged from *suitable* to *unsuitable*. Furthermore, June reached an *excellent* suitability index by only over 2% area.

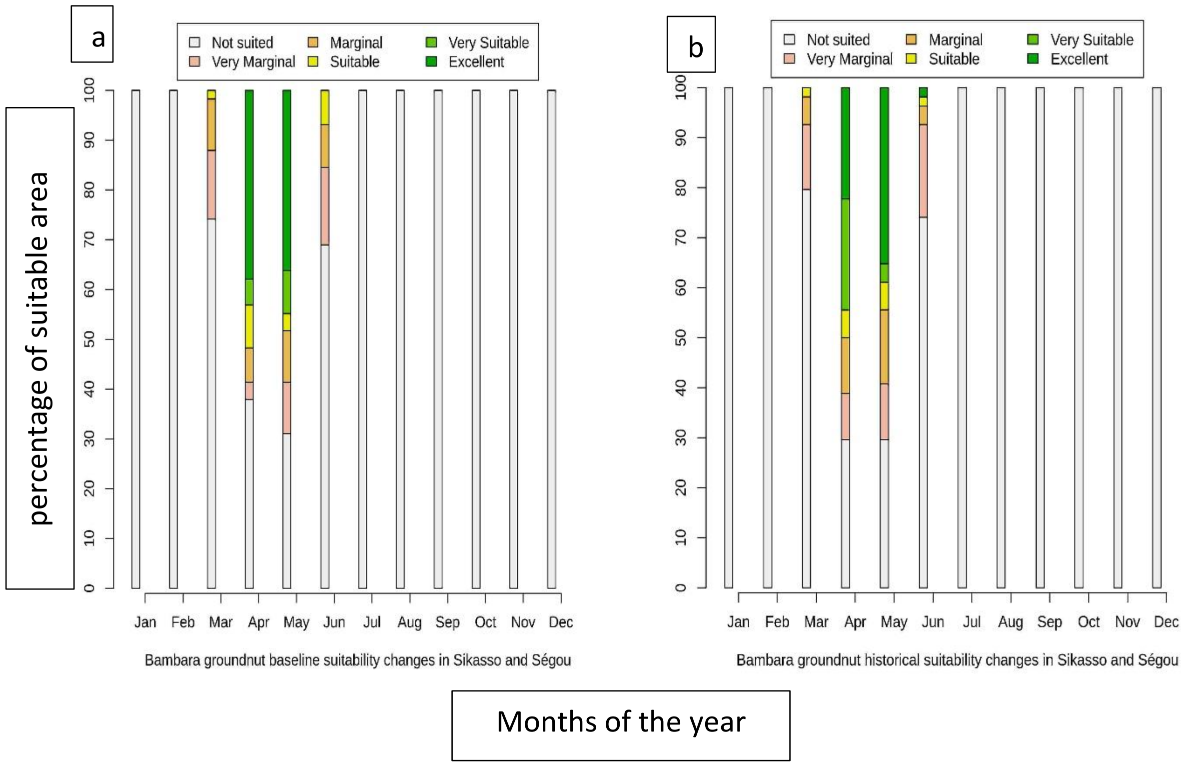

Figure 4.1: Simulated changes in bambara groundnut (a) baseline and (b) historical seasonal suitability in Sikasso and Ségou. The x-axis represents the planting dates (months), and the y-axis represents the cumulative percentage of suitable area.

4.1.2 Baseline and historical spatial suitability

The baseline and historical spatial suitability over Sikasso and Ségou concur with seasonal suitability in March to June as best suited planting dates, with a north to south decreasing gradient from low suitability in the north (Ségou) to high suitability in the south (Sikasso).

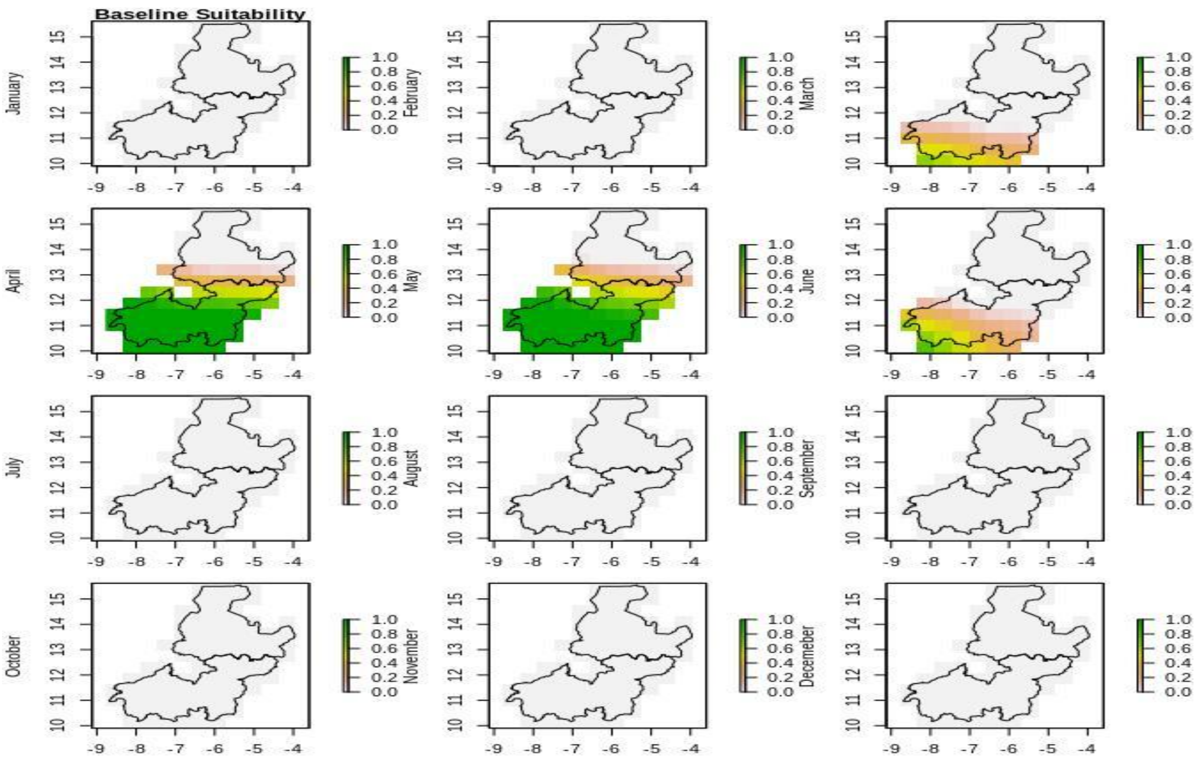

Figure 4.2: Simulated changes in spatial suitability of bambara groundnut baseline in Sikasso (south) and Ségou (north).

In March and June, bambara groundnut was observed to be *suitable* (0.5-0.7) in the lower area of Sikasso (Figure 4.2). This receded to *marginally suitable* (0.3-0.5) in the central area of Sikasso, and further decreased to be *unsuitable* (0-0.1) in the upper area of Sikasso and the whole area of Ségou. The baseline spatial suitability in April and May showed an increase in suitability index in Sikasso and up to the lower area of Ségou. Bambara groundnut suitability in the months mentioned earlier was *excellent* (0.9-1) in the lower and central area of Sikasso. Also, suitable areas expanded to the Ségou region as the suitability index in the lower area of Ségou, from *suitable* (0.5-0.7) to *marginally suitable* (0.3-0.5) which in the previous months had been *unsuitable* (0-0.1). Despite the expansion of suitable area to Ségou, the central and upper areas of Ségou remained *unsuitable* (0-0.1).

The historical spatial suitability (Figure 4.3) concurs well with the baseline spatial suitability, except in March and June, where a small portion in the lower area of Sikasso indicated a high suitability index of *very suitable* (0.7-0.9) in March, and *excellent* (0.9-1) in June. The above results thus show an agreement exists between the simulated baseline and historical suitability, indicating adequate confidence in the crop model for its use in projecting future suitability.

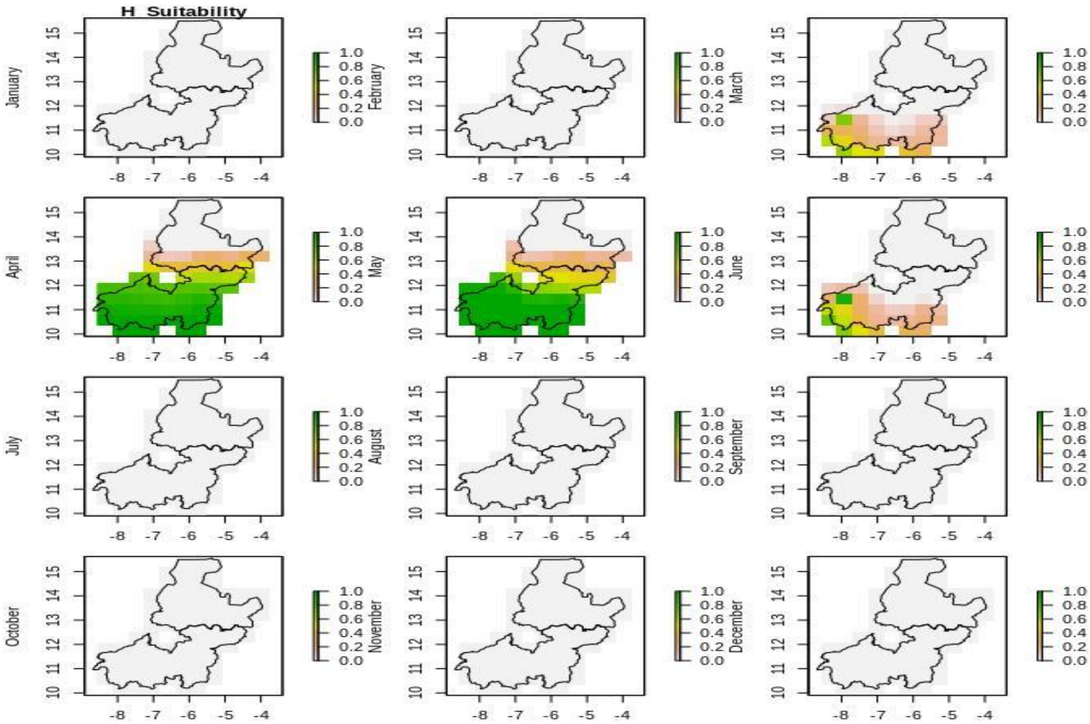

Figure 4.3: Simulated changes in bambara groundnut historical spatial suitability in Sikasso and Ségou.

4.2 Projected changes in seasonal suitability under future climatic projections

4.2.1 Near term seasonal suitability

The projected seasonal suitability of bambara groundnut in near-term (2011-2040) time period (hereafter near-term suitability), shows that the best suited periods for planting bambara groundnut in Sikasso and Ségou remains March to June with other months still *unsuitable* (Figure 4.4) as in historical seasonal suitability (refer to section 4.1.1). With the projected increase in near-term temperature and precipitation projections (figures 3.3 and 3.4), the near-term suitability index and cumulative percentage of suitable areas are projected to increase across all suitable months. However, despite this increase in the cumulative percentage of suitability areas across the suitable months, a decrease in the percentage of suitable areas is projected in April. May is projected to have the highest *excellent* (0.9-1) suitability index followed by April. Also, there is a projected increase in the suitability index in March and June.

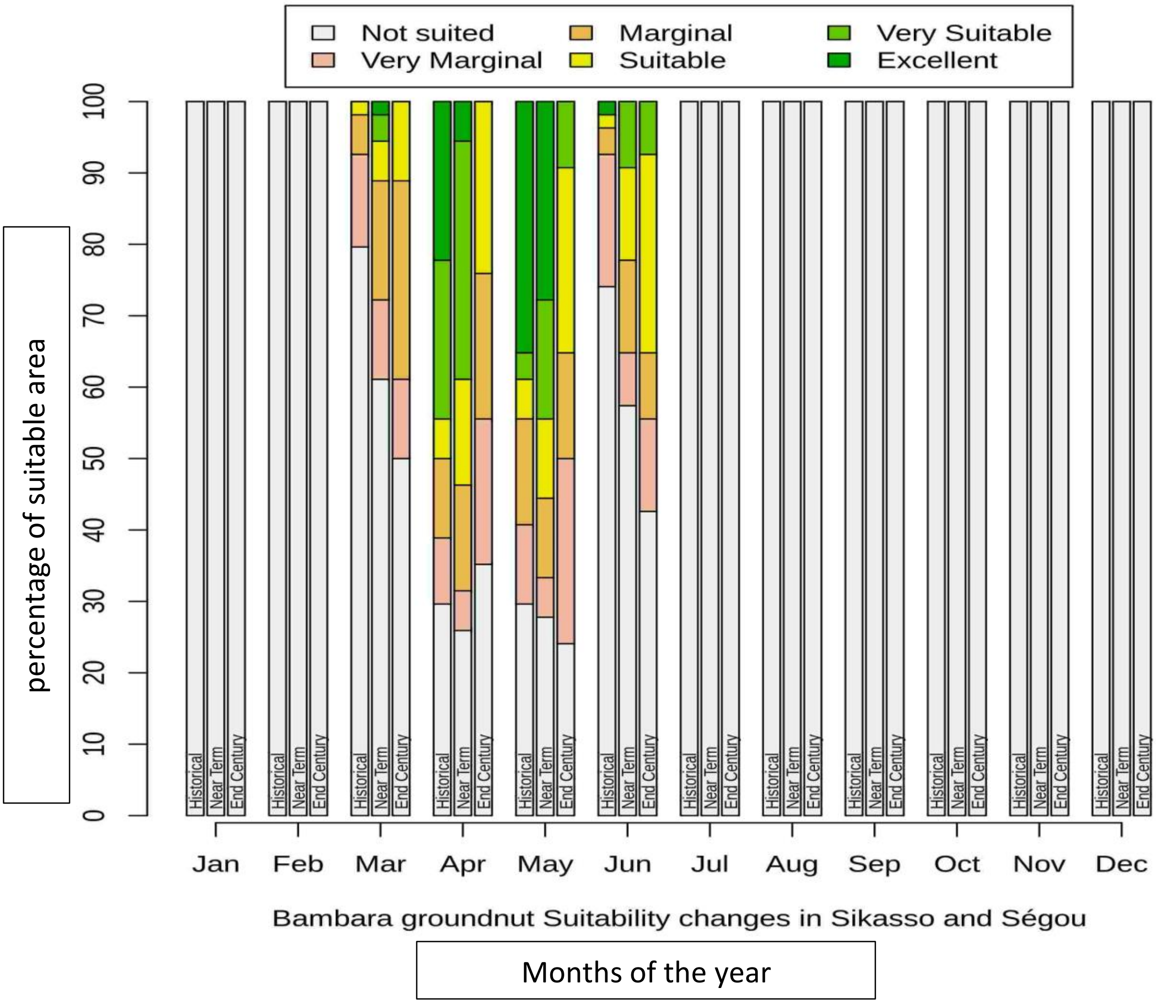

Figure 4.4: Projected changes in the seasonal suitability of bambara groundnut across the past and future climates.

4.2.2 End of century seasonal suitability

By the end of century time period (2070-2099) (hereafter end of century suitability), the model projects no change in the optimal planting months. The end of century seasonal suitability is shown in Figure 4.4 above, reveals a decrease in suitability index across suitable months. This decrease in suitability index may be attributed to the increased amount of precipitation in the months. However, despite the decrease in suitability index, the cumulative percentage of suitable area is projected to increase across months, except in April. Furthermore, by the end of century, seasonal suitability during May and June are the only months with a *very suitable* suitability index.

The projected impact of future climate projections on the seasonal suitability of bambara groundnut over Sikasso and Ségou indicates that the best suitable months for the planting of the crop remained consistent within March to June across the three time periods. The projections further suggest that the regions will experience a decrease in crop suitability index, especially by the end of century, particularly in April. Despite this decrease in suitability index, the overall percentage of the suitable area by the end of century will remain higher than the historical and near-term suitability.

4.3 Projected changes in spatial suitability under future climate projections

4.3.1 Near-term spatial suitability

The near-term spatial suitability projections (Figure 4.5) show the months suitable for planting bambara groundnut remained within March to June. In March, a mixture of various suitability index ranges are projected, varying from *excellent* (0.9-1) to *very suitable* (0.7-0.9), and to *suitable* (0.5-0.7) in the lower area of Sikasso to *marginally suitable* (0.3-0.5) in the central area. While the upper area of Sikasso and the entire area of Ségou are projected to be *unsuitable* (0-0.1). In June, the suitability index is projected to vary from *very suitable* (0.7-0.9) in the lower area of Sikasso to *marginally suitable* (0.3-0.5) in the central area. However, in the lower area of Sikasso, suitable areas are projected to be wider in June than in March. For April and May, an *excellent* (0.9-1) suitability index is anticipated in the lower and central area of Sikasso and *very suitable* (0.7-0.9) in the upper area. While in Ségou, the lower area is expected to be *suitable* (0.5-0.7) and become *marginally suitable* (0.3-0.5) at the central area as upper areas remain *unsuitable* (0-0.1).

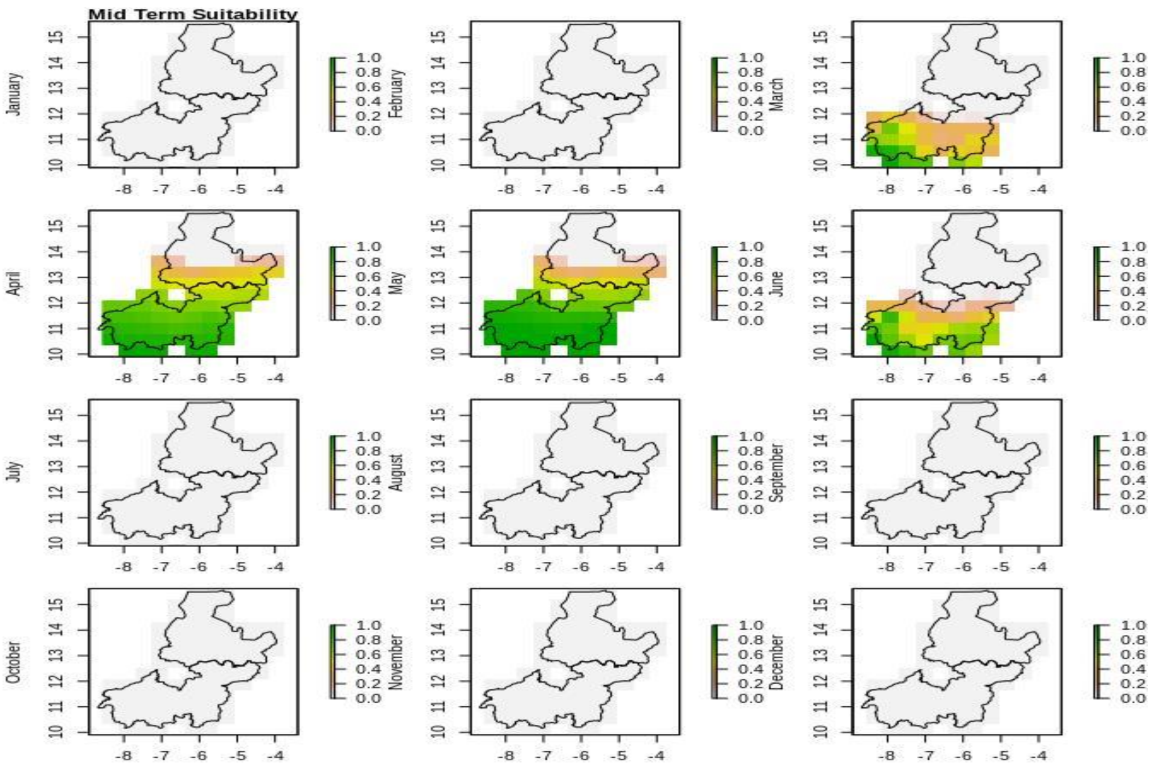

Figure 4.5: Projected near-term spatial suitability of bambara groundnut in Sikasso (south) and Ségou (north).

4.3.2 End of century spatial suitability

The projected end of century spatial suitability (Figure 4.6) indicates that as in the historical (Figure 4.3) and near-term (Figure 4.5) spatial suitability, bambara groundnut's best suitable planting dates (months) will remain within March to June. By the end of century, an expansion in suitable areas is projected across suitable months. The most significant expansion by the end of century spatial suitability is projected to occur in April and May in Ségou. In March, the lower area of Sikasso is projected to be *suitable* (0.5-0.7), and the central area is expected to be *marginally suitable* (0.3-0.5), while the upper area of Sikasso and the entire area of Ségou is projected to be *unsuitable*. For June, the model projects that the lower area of Sikasso will be *very suitable* (0.7-0.9) up to the central area, which in March was *marginally suitable* (0.3-0.5). Also, the upper area of Sikasso, as well as a small portion in the lower area of Ségou, are projected to be *marginally suitable* (0.3-0.5). Apart from this small portion, other areas in Ségou are projected to be *unsuitable* (0-0.1) in March and June. A *very suitable* suitability index (0.7-0.9) is projected for bambara groundnut in the lower area of Sikasso in April and May. This projection is expected to become *suitable* (0.5-0.7) around the central area and *marginally suitable* (0.3-0.5) from the upper area of Sikasso to the lower and central areas of Ségou, which in March and June were *unsuitable* (0-0.1) in historical and near-term suitability. Nevertheless, the suitability projections for the upper area of Ségou is projected to remain *unsuitable* (0-0.1) across the months.

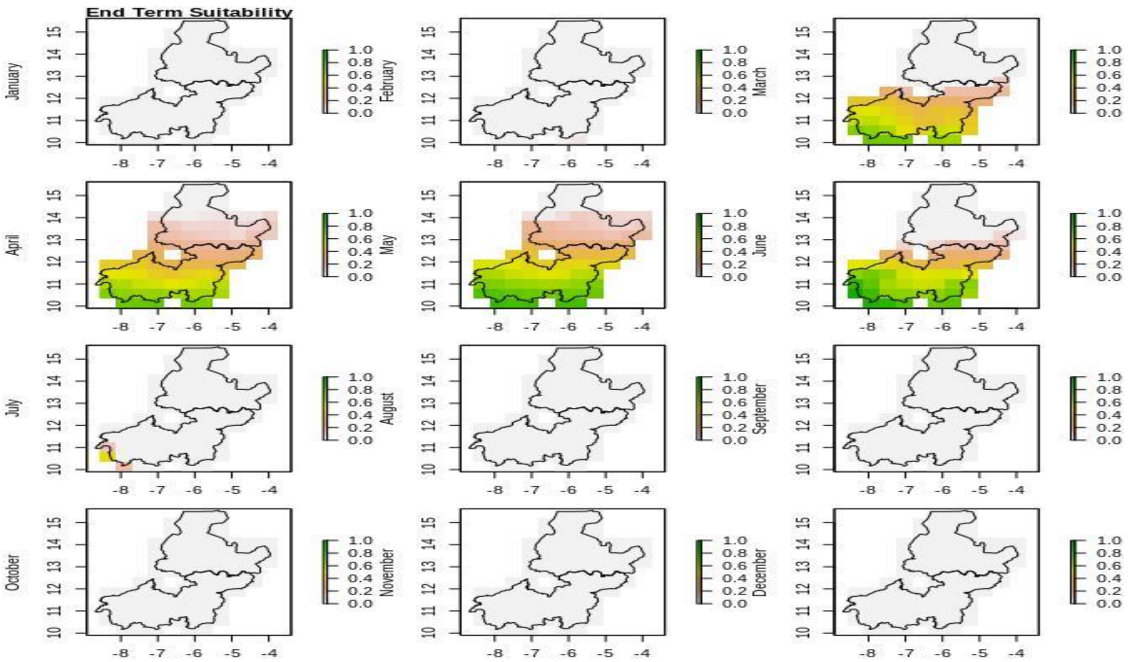

Figure 4.6: Projected end of century (2070-2099) spatial suitability distribution of bambara groundnut in Sikasso and Ségou.

4.4 Difference between the past and future spatial suitability

Although the simulations of bambara groundnut climatic suitability considered the 12 potential growing periods (months), the optimally suited months for planting bambara groundnut in the regions remained within March to June for the past and future suitability. However, to compare the changes in spatial suitability between the time periods, the four best-suited planting dates (months) were selected for the time periods. Two colours (purple and blue) were used to represent the changes in suitability. The purple indicates increased magnitude change in suitability while the blue indicates a decreased magnitude change in suitability index.

4.4.1 Change between near-term and historical spatial suitability

The change between the near-term and historical spatial suitability of bambara groundnut (Figure 4.7) indicates that there will be an increased change in suitability in March and June in Sikasso (south) and April and May in Ségou (north). For March and June, the model projects an increased change in suitability in the lower and central area of Sikasso and no change in the upper area of Sikasso and all of Ségou. Also, the small portion in the lower area of Sikasso that maintained its high suitability index in the months indicates no change in suitability. In April, the lower and central areas of Sikasso show a minimal change in suitability, as the lower area of Ségou shows an increased change in suitability. For May, while the lower and central areas of Sikasso shows no change in suitability, an increased change in suitability is expected in the upper area of Sikasso, and the lower area of Ségou showed a high change in suitability.

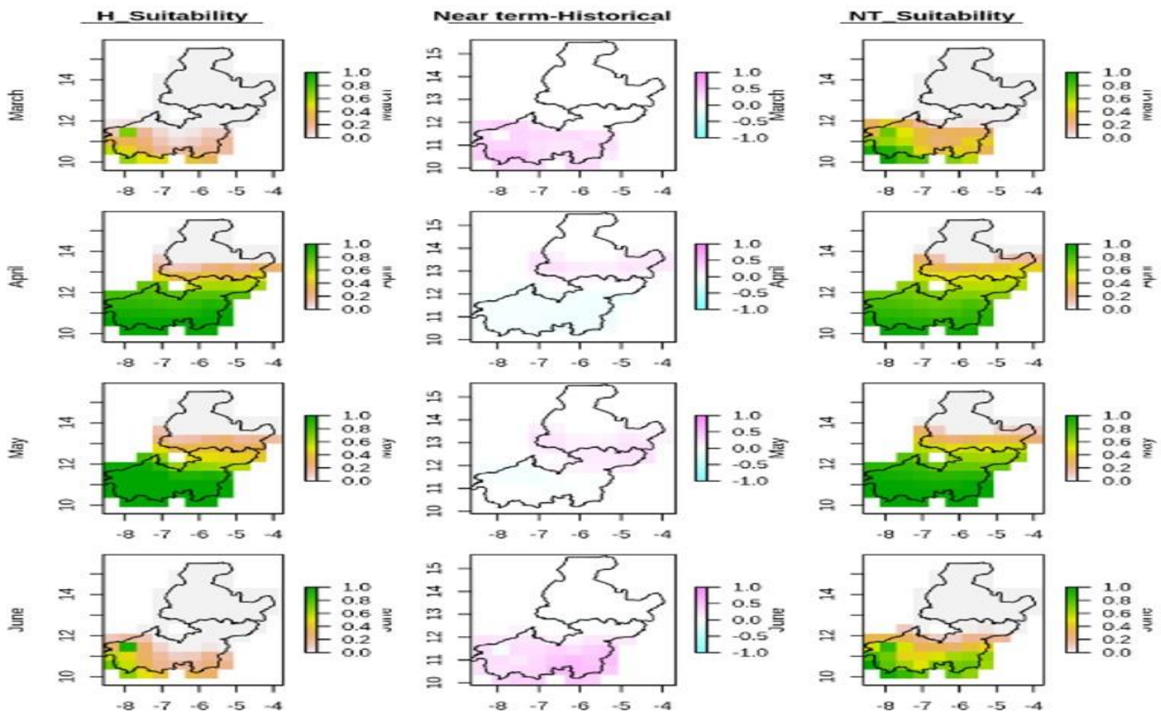

Figure 4.7 Projected difference between historical (H_Suitability) and near-term (NT_Suitability) suitability.

4.4.2 Changes between the end of century and historical spatial suitability

The difference between the end of century and historical spatial suitability (Figure 4.8 above) indicates a substantial increase in suitability in March and June at the lower and central areas of Sikasso and no change in the upper area of Sikasso and the entire area of Ségou. Furthermore, in March and June, a decreased change in suitability is expected over the small portion in the lower area of Sikasso. In April and May, the suitability changes in the lower and central areas of Sikasso, as well as the lower area of Ségou, are projected to be low. While the change in suitability in the central area of Ségou is projected to be high, no change in suitability in the upper area of Ségou is expected.

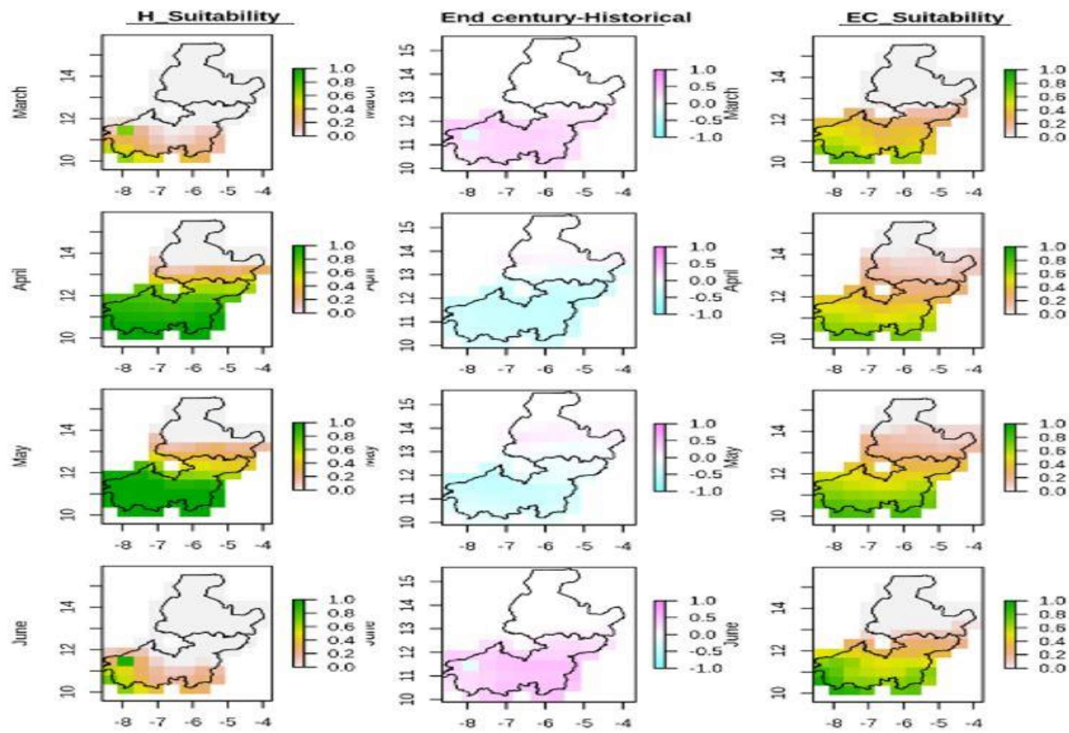

Figure 4.8: The differences between the historical (H_Suitability) and end of century (EC_Suitability) suitability.

Overall, the results suggest that with the projected changes in future climate conditions, the suitability index of bambara groundnut in Sikasso and Ségou will increase, especially in the near-term. This increase in suitability index is projected to decrease by the end of century; however, an expansion in suitable area is projected for the future especially by the end of century which will balance for the decrease in suitability index.

Chapter 5: Discussion

The chapter discusses the results of the changes in climate projection, bambara groundnut seasonal and spatial suitability in the near-term (2011-2040), and the end of century (2070-2099) under RCP 8.5 in Sikasso and Ségou regions, southern Mali. It also covers a discussion between the spatial suitability of bambara groundnut in contrast to three staple crops (maize, sorghum, and millet) in the regions.

5.1 Suitability Projections

5.1.1 Projected seasonal suitability to future climatic projection

The model projects an increase in bambara groundnut seasonal suitability in the future over Sikasso and Ségou regions under the changing climate, partly due to the early onset and marginal increase in precipitation as well as an increase in temperature in the suitable months. There is also a clear indication that in the regions, bambara groundnut has more suitability potential by the end of century than the near-term due to the increase in suitable areas, despite the reduction in suitability index (*excellent, very suitable, suitable, marginally suitable* and *not suitable*). This increase in suitable areas by the end of century is a result of the increase in rainfall while the temperature remains consistently high in suitable months. Additionally, this indicates that while bambara groundnut is sensitive to the increase in temperature, it will be more sensitive to the mild increase in precipitation, especially in April and May than in March and June. The high sensitivity of bambara groundnut to temperature in April and May suggest that the temperature in these months is at ±40^{o}C, which exceeds the optimal maximum temperature threshold of 38^{o}C stipulated for bambara groundnut planting according to the FAO-Ecocrop database (FAO,2000).

The seasonal suitability index over the regions in near-term remained high across the suitable months, especially in April and May. However, the suitability index in April and May by the end of century reduced, as the suitable areas increased in all the months expect in May as a result of the increase in temperature, which does not exceed the optimal maximum temperature and the increase in precipitation. Furthermore, the future climatic projections over Sikasso and Ségou within July to October show a high temperature and high precipitation likely to result in a hot and wet climate, whereas November to February shows high temperature and low precipitation, likely to result in a cool and dry climate, suggesting a potential widening of seasonal suitability to the latter months.

5.1.2 Changes in projected spatial suitability to future climatic projections

The assessment of the spatial suitability of bambara groundnut in the regions indicates that in the near-term and by the end of century, there is a high agreement that Sikasso (south) will have a higher suitability index than Ségou (north) across the suitable months and time periods, as the climate in Ségou is projected to be warmer than Sikasso. However, with the increase in precipitation, Ségou will experience a warm climate that will result in an increase in suitability index and widening of suitable area. Furthermore, despite the Sikasso region having higher suitability, which is projected to remain consistent in the future, suitability index range and areas in Ségou are potentially expected to increase, especially by the end of century, implying a future potential for the crop in the region.

The results of this study thus reveal that bambara groundnut is sensitive to changes in future climatic projections in Sikasso and Ségou, based on seasonal and spatial suitability changes. In addition, the suitability index is estimated to be higher by the near-term than by the end of century. However, this reduction suitability index by the end of century is projected to be replaced with the widening in a suitable area. In Sikasso and Ségou, the *unsuitable* areas do not imply that the crop cannot grow in the areas, it merely indicates the production rate of the crop is expected to be higher in the areas where the suitability index was recorded.

5.2 Relating simulation to observed crop yield and timing

The three-year bambara groundnut field experiment data from six communities in Sikasso (Finkoloni, N'Goutjina, Siramana) and Ségou (Somo, Bolimasso, Boumboro) (shown in Figure 3.7) was used as an observation to assess the capability of the crop model in capturing the suitability of the crop. The results from the simulation highlight that the crop model did not accurately capture the traditional planting date (months) of bambara groundnut in the regions, which is often June-September, instead the model captured March-June (Figure 5.1) as the suitable dates for the planting of the crop. An email (A. Sidibe 2019, personal communication,2 May) confirmed that the planting of bambara groundnut in Sikasso and Ségou do not have specified dates, as it is an underutilised crop. However, when the farmers decide to plant the crop, it often takes place within June/July and harvested in September.

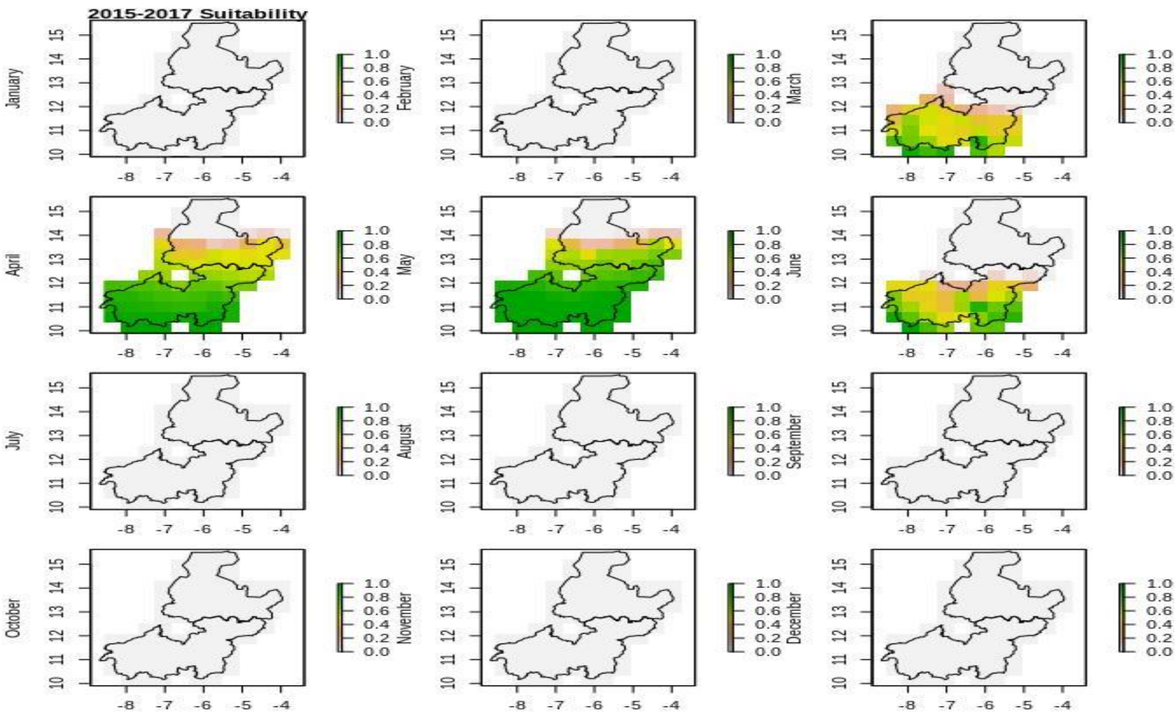

Figure 5.1: Spatial distribution of areas suitable for bambara groundnut production in 2015-2017.

As the suitability rating of the model offers some relation to crop yield (Ramirez-Villegas *et al*., 2013; Jarvis *et al.* 2012), the bambara groundnut yield data (Table 5.1) shows that a higher yield was recorded in Sikasso compared to the yield in Ségou, corresponding with the suitability output from the model (Figure 5.2). Given this, the model is said to have accurately captured the planting window length despite the variation in planting dates (months) and further adequately captured the suitability index and suitable areas.

Table 5.1: Bambara groundnut yield rate (kg/ha)

	2015	2016	2017
Sikasso	40.00	41.37	30.53
Ségou	19.35	23.80	23.77

Another critical observation from the results is the small area in the left area of the Sikasso region that remained highly suitable across the past and future climate period as well as in the crop yield simulation. The high suitability of the area as mentioned earlier can be attributed to the presence of Sélingué dam located within the area, the Sélingué dam is an artificial dam built in 1980 on the Sankarani River, a tributary of the Niger River (Perga, Arfi and Gerdeaux, 2005). Although the climate in the Sikasso was warm, the land surrounding the dam has a high soil moisture rate, which is maintained by the presence of the dam, hence the high suitability in the area. Also, the root depth and biomass in legume crops are known to allow for adequate soil moisture, and nutrient extraction and retention (Blum, 2011; Fenta *et al.*, 2014). Hence, the root system development and distribution of bambara groundnut can be a factor that contributed to the sustained suitability of the crop (Azam-Ali *et al.*, 2001; Mwale *et al*., 2007; Gaur, Krishnamurthy, and Kashiwagi, 2008).

5.3 Implication and limitation of the study

5.3.1 Projections of climate in Sikasso and Ségou

The climatic projections from the CORDEX climate simulations used for this study indicate that in the near-term and by the end of century time periods under RCP 8.5, Sikasso (south) and Ségou (north) regions will experience a high increase in monthly temperature and a marginal increase in monthly precipitation. These changes in monthly temperature and precipitation conditions are expected to result in a warmer climate in Sikasso; however, the warming climate is projected to become more intense northwards in Ségou. These climate projections are likely to have a substantial positive effect on bambara groundnut suitability in the regions, as the crop tolerates a high range of increasing temperatures and low precipitation given the ecological threshold (Table 3.2) of the crop, creating a prospect for promotion of the crop as a climate-resilient crop.

5.3.2 Projected planting window

The past and future suitability of bambara groundnut indicate a long planting window for the crop in Sikasso and Ségou, allowing for multiple planting dates (months). The availability of multiple planting dates imply that the crop can be planted within any of the suitable dates, thus providing an opportunity for bambara groundnut farmers to benefit from a longer planting window and potentially high crop yield. For instance, Berchie *et al.*, (2016) reports that in Tono-Navrongo, Upper East region of Ghana under multiple sowing dates bambara groundnut had a high pod and seed yield of between 600kg/ha to 5.5 t/ha and 420kg/h to

3.8t/ha under lower precipitation season in February. Hence, multiple and longer planting window increases the opportunity of high crop production for farmers and an opportunity for crop rotation with other crops.

5.3.3 Model limitation

The deviations between the model suitability simulation from the crop yield data could be a result of the differences in landrace and genetic information of crops used in the field experiment, which the Ecocrop model does not consider or provide for. The Ecocrop model only accounts for suitability of a crop and has no appreciation of crop dynamics, biophysical factors, pests, and diseases which is an issue with empirical models in general. For instance, the Sélingué dam, which contributed to the high suitability of bambara groundnut in Sikasso but was captured by Ecocrop suitability model. Therefore, considering these limitations, the study focused on presenting the changes in seasonal and spatial suitability which were well captured by the model.

Chapter 6: Conclusion

This study enhances the understanding of underutilised crops while focusing mainly on bambara groundnut, a type of underutilised crop, and assessing how future climatic projections will affect the suitability of the crop in Sikasso and Ségou situated in southern Mali, West Africa. This study also discussed the spatial suitability of bambara groundnut in contrast to staple crops (maize, millet, and sorghum) in the regions. 10 bias corrected CORDEX data under RCP 8.5 were used to drive the Ecocrop suitability model at a local scale. The three climate variables used in the study were total monthly precipitation, monthly minimum, and mean temperature. Suitability simulations were run for three time periods, one past-historical (1975-2005), and two future: near term (2011-2040), and end of century (2070-2099). Driven by monthly minimum and mean temperature, and total monthly precipitation over each selected time period, the seasonal and spatial suitability of bambara groundnut was analysed using suitability index ranges from 0 (unsuitable) to 1 (optimal suitability).

6.1 Key results

Under the Representative Concentration Pathway (RCP) 8.5, the CORDEX data projects a 1.5 to 4.5^{o}C increase in temperature for the monthly minimum and mean temperatures from near-term to end of century over Sikasso and Ségou, while precipitation projections indicate a mild increase over these regions.

This study establishes a variation in the seasonal and spatial suitability projections of bambara groundnut, attributed to the changes in future climate projections. However, the impact of future climate projections on the suitability of bambara groundnut is suggested to be positive. bambara groundnut shows a progressively strong positive response to future climatic projections through the near-term to end of century and an increase in suitability from Sikasso (south) to Ségou (north).

The seasonal suitability of bambara groundnut indicates long planting dates for the crop, as the best planting dates (months) for the crop are between March-June, the months with less precipitation. The long planting dates increase the opportunity of a high production rate as the farmers can plant in any of the suitable dates and have the opportunity of planting multiple times.

The results of this study also suggest an increase in the spatial suitability of bambara groundnut in the future (near term and end of century), especially by the end of century. Furthermore, Sikasso maintained its high spatial suitability rating across the time periods, the low spatial suitability rating in Ségou is expected to increase, especially in April and May, by the end of century. Overall, with the suitability projection results taken into consideration, there is high confidence in an increase in the suitability of bambara groundnut over Sikasso and Ségou in the future.

When comparing the spatial suitability of bambara groundnut to that of staple crops, bambara groundnut shows a higher chance of an increase in suitability in areas where staple crops' suitability is likely to reduce. Thus, the projected increase in the seasonal and spatial suitability of bambara groundnut has a favourable implication for the farmers in the regions, the agricultural sector as well as the food system in Mali, especially as southern Mali is known to be the agricultural hub of the country where most farming activities take place.

6.2 Enhancing the production and utilisation of underutilised crops

The increasing dependency of crop production on a few staple crops is increasing the pressure on these crops and continues to increase as the demand for food increases, especially in the face of climate change. To help address this unequal dynamic in the food system with the learning from this study, there is a need to facilitate attitude change towards the underutilised crops and its utilisation. Strategic approaches that could contribute to improving the utilisation of underutilised crops include:

6.2.1 Inclusion of underutilised crops into food security agenda

The required changes needed for sustainability in the food system could require the contribution of underutilised crops. For instance, the high nutritional values of bambara groundnut create an avenue for the inclusion of the crop in the list of food crops that can contribute to addressing food and diet security issues.

6.2.2 Adaptive and inclusive crop system

An adaptive and inclusive crop system should have the ability to accommodate all varieties of crops. However, the crop system currently focuses mainly on staple crops such as maize, rice, wheat, groundnut, and sorghum. With the projected increased negative impact of climate change on these staple crops, a sustainable crop system that is diversified and adaptive to climate change will enhance food production and provide the farmers with a variety of crops to cultivate.

6.2.3 Planting date knowledge

For underutilised crops, because they are rarely cultivated, limited knowledge exists on its planting dates often resulting in the non-consideration of suitable growing seasons. The non-consideration of suitable planting dates when planting underutilised crops sometimes contributes to the crop's low yield and could likely be a contributing factor to the underutilisation of the crops. Thus, extensive knowledge of the planting dates of underutilised crops will help create more opportunities for a high yield rate.

6.3 Value of the study

This study has reinforced the knowledge on the climatic suitability of underutilised crops to climate change, the roles they can play in diversifying the food system as well as benefits of smallholder farmers in cultivating underutilised crops in Africa. Thus, for sustainability in the food system, policies on adequate utilisation of underutilised crops should be introduced as an alternative food source towards achieving food security.

This study has enhanced our understanding of the use of the crop model to evaluate the future suitability projections of bambara groundnut. However, this study can be improved through an explicit investigation of the interaction of underutilised crops and other environmental factors such as solar radiation, land-use change, and atmospheric CO_2. The result will enhance the knowledge of the impact of various environmental factors on the crop.

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